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THESIS

BANK-TO-TURN CRUISE MISSILE TERMINAL GUIDANCE AND CONTROL LAW COMPARISON

by

Kent B. Watterson

June 1983

Thesis Advisor: Marle D. Hewett

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Bank-To-Turn Cruise Missile Terminal Guidance and Control Law Comparison

by

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Lieutenant Commander, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING SCIENCE

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SYMBOLS AND ABBREVIATIONS

U	Linear Velocity along body x axis
V	Linear Velocity along body y axis
W	Linear Velocity along body z axis
P	Roll rate
Q	Pitch rate
R	Yaw rate
X	Aerodynamic force in body x direction
Y	Aerodynamic force in body y direction
Z	Aerodynamic force in body z direction
Φ	Bank angle
Θ	Pitch angle
Ψ	Yaw angle
X_E	Earth coordinate of missile (Latitude)
Y_E	Earth coordinate of missile (-Longitude)
$-Z_E=H_E$	Earth coordinate of missile (Altitude)
L_A	Rolling Moment about x axis (Aerodynamic)
M_A	Pitching moment about y axis (Aerodynamic)
N_A	Pitching moment about z axis (Aerodynamic)
V_T	Total missile velocity
T	Thrust
$\bar{q}$	Dynamic pressure ($\frac{1}{2}\rho V_T^2$)
α	Angle of attack
β	Side slip angle

γ	Flight path angle ($\theta + \alpha$)
ρ	Air density (0.002377) slug/ft^3
S	Wing area (12 ft.^{2})
b	Wing span (8.485 ft.)
$\bar{c}$	Mean aerodynamic chord (1.414 ft.)
η	Elevator Deflection
ξ	Aileron Deflection
ζ	Rudder Deflection
η_L	Left Stabilator Deflection
η_R	Right Stabilator Deflection
L	Lift force
D	Drag force
N	Normal force
C	Chord wise force
m	Missile mass (68.38 slugs)
g	Acceleration due to gravity (32.17 ft/sec^2)
ST	Static coefficient
DYN	Dynamic coefficient
n_z	Normal load factor (body fixed axis system)*
n_y	Lateral load factor (body fixed axis system)*
n_Z	Vertical load factor (earth fixed axis system)*
n_Y	Horizontal load factor (earth fixed axis system)*
u	Perturbed linear velocity x axis *
v	Perturbed linear velocity y axis *
w	Perturbed linear velocity z axis *

p	Perturbed angular velocity about x axis *
q	Perturbed angular velocity about y axis *
r	Perturbed angular velocity about z axis*
ϕ	Perturbed Euler angle Φ *
θ	Perturbed Euler Angle Θ *
ψ	Perturbed Euler Angle Ψ *
*	Laplace transforms of these variables are shown in capital letters

SUBSCRIPTS

SS	Steady State
E	Earth
B	Body
x,y,z	In body fixed axes
X,Y,Z	In earth fixed axes
T	Due to thrust/Target
A	Due to Aerodynamic Forces
xx,yy,zz	About the axis specified
ST	Steady State
DYN	Dynamic
EL	Eleration
AZ	Azimuth
c	Commanded

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I. INTRODUCTION

The relative merits of bank-to-turn versus skid-to-turn missiles have been argued for years. Bank-to-turn missiles which must roll to a commanded bank angle before a lateral acceleration can be commanded in the appropriate direction are inherently slower to respond to target maneuvering than skin-to-turn missiles of comparable lateral acceleration capabilities. This is particularly true if the bank-to-turn missile has limited roll authority or limited roll rate capability. On the other hand, as discussed in Gonzalez, {Ref. 1}, it is sometimes difficult to build a skid-to-turn missile which meets certain operational goals and performance criteria and also has sufficient control authority in both the y and z directions to generate the large lateral accelerations required to perform skid-to-turn.

In this thesis the terminal guidance accuracy of a bank-to-turn cruise missile is studied for a sea launched, sea target cruise missile of conventional wing-tail configuration. It is assumed that roll authority is extremely limited due to operational design restrictions which impose the use of low authority ailerons or differential stabilator (no ailerons) for rolling. Lateral acceleration is also assumed to be extremely limited in the y direction due to the presence of only a small vertical surface at the tail (vertical stabilizer and rudder).

Two bank-to-turn guidance schemes are compared for accuracy against a medium sized combatant ship employing electronic countermeasures (an ECM blinker mounted aft on the ship). The first baseline scheme employs a pop-out maneuver consisting of a low altitude run in, azimuth offset, pop-up and roll into the target using proportional navigation in azimuth and elevation. The second, or sea-skimmer scheme, employs a straight-in low altitude attack. Miss distances for both schemes are compared while varying missile roll rate limit, ECM blinking frequency and burn through ranges.

A CSMP III simulation was coded to perform the study. Missile dynamics were represented by 6 degree of freedom nonlinear equations of motion with table look-up aerodynamic coefficients. These coefficients are representative of a generic cruise missile with a conventional wing-tail configuration of limited roll authority. Inner loop augmentation and autopilot modes were designed to improve missile damping in all axes, provide commanded load factor, commanded bank angle, and turn coordination. Autopilot outer loops were designed to provide altitude hold, and vertical flight path angle hold. Guidance loops were designed to provide proportional navigation in elevation and azimuth.

Since this study involves the influence of flight dynamic parameters (roll rate limits) on terminal guidance accuracy, no extensive tracker modeling is employed in the simulation. It is assumed that the seeker always tracks

the point target perfectly. The point target is, however, moved by an ECM blinker and contaminated with a glint model.

In Chapter II the equations used to represent missile dynamics are presented along with the methodology used to build up aerodynamic forces and moments. In Chapter III the development, design and simulation of the missile autopilot modes are presented. In Chapter IV the design of the guidance systems and a complete description of the two guidance schemes is presented. In Chapter V the CSMP simulation is presented followed by the results and conclusions of this study.

II. DEVELOPMENT AND SIMULATION OF MISSILE DYNAMICS

In this chapter the linear and nonlinear mathematical models are developed which are used to describe the flight dynamics of a generic bank-to-turn cruise missile. The linearized mathematical model of missile dynamics is used to design the missile autopilot control laws and guidance laws. The nonlinear mathematical model is used to accurately represent missile dynamics in a CSMP computer simulation of a sea launched generic cruise missile attacking a medium sized combatant ship. Since the purpose of this investigation is to perform a detailed evaluation of terminal control laws, it was decided that a linear dynamic simulation would not adequately represent missile motion; hence a full six degree of freedom (6 DOF) nonlinear dynamic simulation was encoded. The overall system that is modeled in this study is depicted in block diagram format in Figure 2-1 and will be developed in this thesis.

A. MISSILE EQUATIONS OF MOTION

The full nonlinear six degree of freedom rigid body, dynamic equations of motion are used to represent the motion of a generic bank-to-turn cruise missile. The aerodynamic forces and moments are built up from representative tabular coefficient data for the generic missile. These tabular

data are given in Appendix A in graphical form along with the generic missile's physical and geometric characteristics.

1. Assumptions

The assumptions used in the development of the equations of motion are given below.

a. The earth is flat, does not rotate, and is fixed in inertial space.

b. The mass of the missile is constant.

c. The missile is a rigid body.

d. The mass distribution of the missile is constant.

e. Engine angular momentum is neglected.

f. The missile is symmetric about the body's xy plane. Therefore, the products of inertia I_{xy} and I_{yz} are zero.

g. The engine thrust line is parallel to the missile body x axis. Thus, the thrust components T_y and T_z are zero.

h. The density of the atmosphere is constant.

i. The engine thrust line passes through the missile center of mass. Therefore, the moments due to thrust L_T, M_T and N_T are zero.

j. The wind is calm.

k. Right aileron trailing edge down is positive deflection. Negative elevator deflection yields nose up pitching moment (positive).

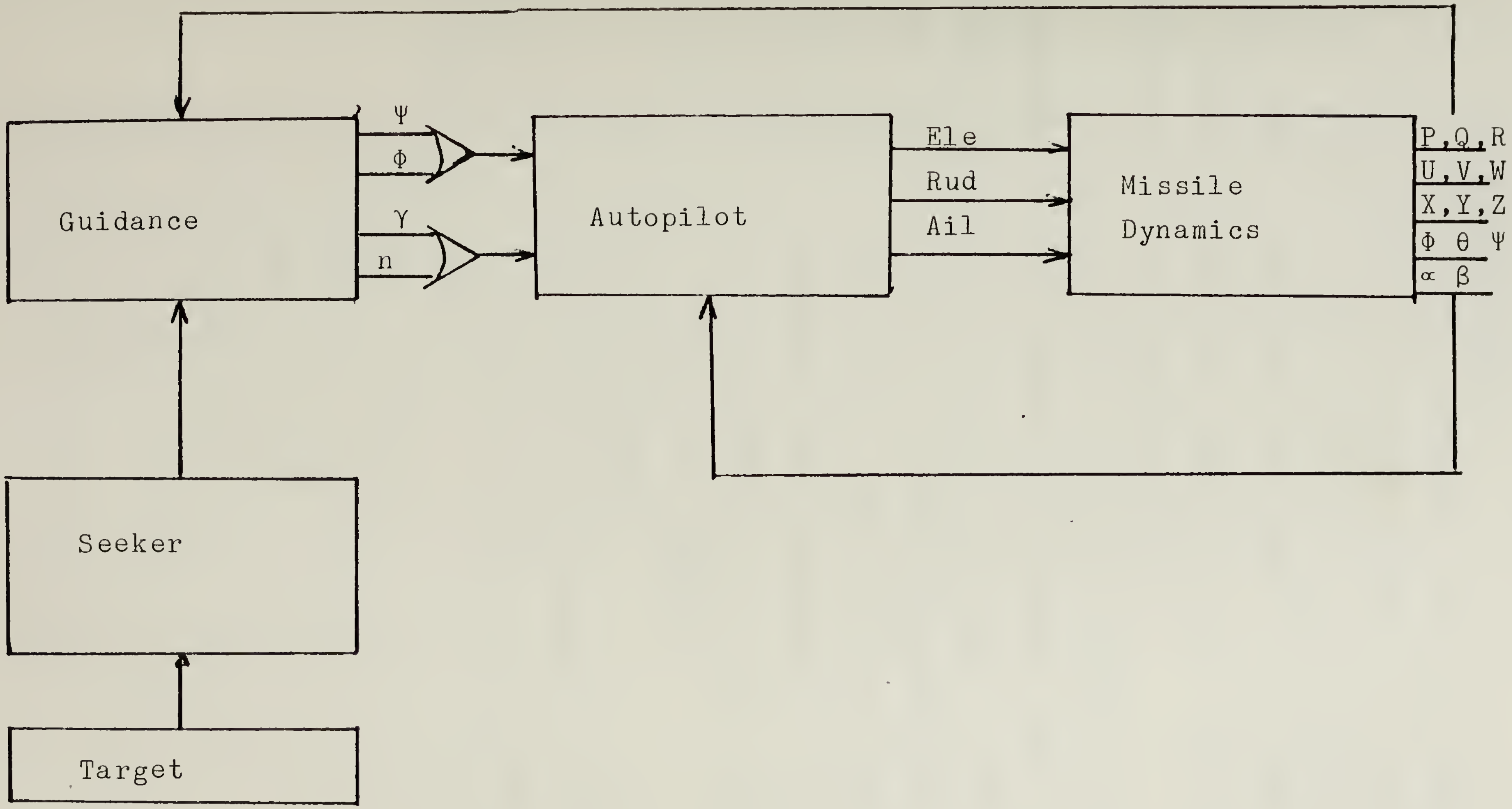


Figure 2-1 Missile System Flow Diagram

2. Coordinate System

An earth fixed coordinate system is established with its origin fixed at the initial position of the missile. The X_E axis points to true north, the Y_E axis points east, and the Z_E axis points toward the center of the earth. Altitude (H) therefore equals the negative of Z_E. The system is considered to be an inertial system.

A stability axis coordinate system is used with coordinates x, y, z fixed at the missile center of mass and oriented such that the x axis lies along the vehicle's forward velocity vector in steady state balanced cruise flight at 0.75 Mach number. The y axis is chosen perpendicular to the plane of symmetry and is oriented out the right wing. The z axis is chosen perpendicular to the x axis in the down direction and in the plane of symmetry.

3. The Equations of Motion

The following nonlinear equations as developed by Hewett {Ref. 2} describe the motion of the missile in 6 degrees of freedom.

$$m\,(\dot{U}-VR+WQ) = -mg \sin \theta + X + T \qquad (1a)$$

$$m\,(\dot{V}+UR-WP) = mg \sin \Phi \cos \theta + Y \qquad (1b)$$

$$m\,(\dot{W}-UQ+VP) = mg \cos \Phi \cos \theta + Z \qquad (1c)$$

$$\dot{P}I_{xx}-(\dot{R}+PQ)I_{xz}+ RQ(I_{zz}-I_{yy}) = L_A \qquad (2a)$$

$$\dot{Q}I_{yy}+PR(I_{xx}-I_{zz}) + (P^2-R^2)I_{xy} = M_A \qquad (2b)$$

$$\dot{R}I_{zz}-\dot{P}I_{xz}+PQ(I_{yy}-I_{xx})+QRI_{xz} = N_A \qquad (2c)$$

$$\dot{\Phi} = P+(Q \sin \Phi + R \cos \Phi) \tan \theta \qquad (3a)$$

$$\dot{\theta} = Q \sin \Phi - R \sin \Phi \qquad (3b)$$

$$\dot{\Psi} = (Q \sin \Phi + R \cos \Phi) \sec \theta \qquad (3c)$$

Equations (1a), (1b) and (1c) describe the translational motion of the missile. Equations (2a), (2b), and (2c) represent the rotational motion. Equations (3a), (3b) and (3c) are the Euler relations for bank, pitch and yaw angles.

Equations (4a), (4b), and (4c) describe the missile's position referenced to the earth fixed system (X_E, Y_E, Z_E).

$$\dot{X}_E = U \cos \Psi \cos \theta + V(\cos\Psi \sin\theta \sin\Phi - \sin\Psi \cos\Phi) \qquad (4a)$$
$$+ W(\cos\Psi \sin\theta \cos\Phi + \sin\Psi \sin\Phi)$$

$$\dot{Y}_E = U \sin \Psi \cos \theta + V(\sin\Psi \sin\theta \sin\Phi + \cos\Psi \cos\Phi) \qquad (4b)$$
$$+ W(\sin\Psi \sin\theta \cos\Phi - \cos\Psi \sin\Phi)$$

$$\dot{Z}_E = U\sin\theta - V\cos\theta \sin\Phi - W\cos\theta \cos\Phi \qquad (4c)$$

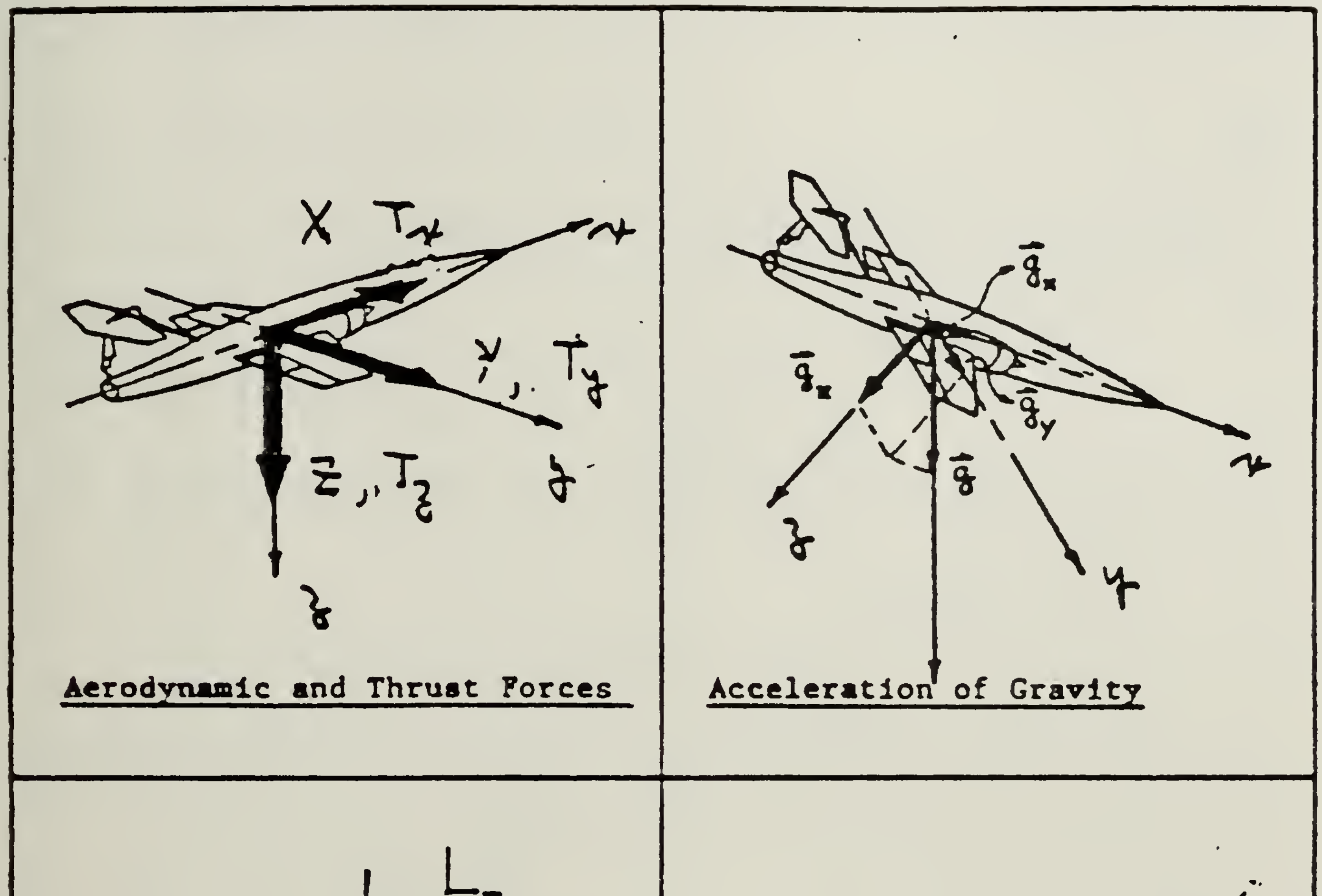
Equations (5), (6) and (7) are also required. Equations (5) and (6) yield angle of attack and side slip angle respectively in terms of velocity components U, V and W. Equation (7) represents the total velocity of the missile.

$$\alpha = \arctan \frac{W}{U} = \arcsin \frac{W}{(U^2+W^2)^{\frac{1}{2}}} \qquad (5)$$

$$\beta = \arctan \frac{V}{U^2+w^2} = \arcsin \frac{V}{(U^2+V^2+W^2)^{\frac{1}{2}}} \qquad (6)$$

$$V_T = (U^2+V^2+W^2)^{\frac{1}{2}} \qquad (7)$$

Figure 2-2 illustrates the positive directions and locations of forces, moments and velocities in the body coordinate system (x, y, z).



Aerodynamic and Thrust Forces

Acceleration of Gravity

Aerodynamic and Thrust Moments

Linear and Rotational (Angular) Velocities

Figure 2-2 Body Coordinate System Description

Equations (1a), (1b), (1c) and (2a), (2b), (2c) can be rewritten in state format as follows:

$$\dot{U} = -g\sin\theta + VR - WQ + \frac{X}{m} + \frac{T}{m} \qquad (8a)$$

$$\dot{V} = g\sin\Phi\cos\theta - UR + WP + \frac{Y}{m} \qquad (8b)$$

$$\dot{W} = g\cos\Phi\cos\theta + UQ - VP + \frac{Z}{m} \qquad (8c)$$

$$\dot{P} = \left[L_A I_{zz} + N_A I_{xz} - PQ(I_{yy} - I_{xx} - I_{zz})I_{xz} - RQ(I_{zz}^2 - I_{yy}I_{zz} + I_{xz}^2)\right] / (I_{xx}I_{zz} - I_{xz}{}^2) \qquad (9a)$$

$$\dot{Q} = \left[M_A - PR(I_{xx} - I_{zz}) - (P^2 - R^2)I_{xz}\right] / I_{yy} \qquad (9b)$$

$$\dot{R} = \left[L_A I_{xz} + N_A I_{xx} - PQ(I_{yy}I_{xx} - I_{xx}^2 - I_{xz}^2) - RQ(I_{xx} + I_{zz} - I_{yy})I_{xz}\right] / (I_{xx}I_{zz} - I_{xz}^2) \qquad (9c)$$

Now integrating equations (3), (4), (8) and (9) results in U, V, W, P, Q, R, Φ, θ, Ψ, X_E, Y_E and Z_E (-H). The missile's velocities, angular rates, and angles and positions have thus been described.

4. Trim Equations

For straight and level flight at constant velocity the following variables are all zero: $\dot{U}$, $\dot{V}$, $\dot{W}$, $\dot{P}$, $\dot{Q}$, $\dot{R}$, $\dot{\Phi}$, $\dot{\theta}$, $\dot{\Psi}$, $\dot{Z}_E$, P_{SS}, Q_{SS}, R_{SS}, Φ_{SS}, $L_{A_{SS}}$, $N_{A_{SS}}$, Y_{SS}, γ_{SS}, β_{SS}, V_{SS}, $M_{A_{SS}}$ Thus the trim equations reduce to:

$$X_{SS} + T_x = mg\ \sin\theta_{SS}$$

$$Z_{SS} = -mg\ \cos\ \theta_{SS}$$

$$\dot{X}_{E_{SS}} = U_{SS}\cos\Psi_{SS}\cos\theta_{SS} - V_{SS}\sin\Psi_{SS} + W_{SS}\cos\Psi_{SS}\sin\theta_{SS}$$

$$\dot{Y}_{E_{SS}} = U_{SS}\sin\Psi_{SS}\cos\theta_{SS} + V_{SS}\cos\Psi_{SS} + W_{SS}\sin\Psi_{SS}\sin\theta_{SS}$$

$$\tan\theta_{SS} = W_{SS}/U_{SS}$$

$$V_{T_{SS}} = (U_{SS}^2 + W_{SS}^2)^{\frac{1}{2}}$$

Since bank angle equals zero and the sum of flight path angle and angle of attack equal the pitch angle, then in steady state pitch angle equals angle of attack.

$$\theta_{SS} = \alpha_{SS}$$

These equations are used to define the initial cruise condition of the missile which is low level straight and level cruise flight at 0.75 Mach number. The precise initial flight condition and initial target position is described in Appendix B.

5. Other Useful Relations

Components of load factor at the missile center of mass in the y and -z directions are given below:

$$n_z = \frac{-Z}{mg} = \frac{V_T}{g} (Q - \dot{\alpha}) \qquad (10a)$$

$$n_y = \frac{Y}{mg} = \frac{V_T}{g} (\dot{\beta} + R) \qquad (10b)$$

6. Definition of Controls and Control Limits

The control configuration considered in the thesis is a conventional wing and tail with conventional rudder (ζ), aileron (ξ) and elevator (η) control surfaces. In addition, to cover a missile configuration which uses

differential horizontal stabilizer (stabilator) for roll control as opposed to aileron, the quantities left stabilator deflection (η_L) and right stabilator deflection (η_R) are defined and calculated.

Limits are imposed on rudder, elevator, and aileron travel. Limits are not imposed on differential stabilator travel but stabilator travel is presented for all simulations to show the stabilator travel required if indeed that were the control configuration. The aileron power coefficient data presented in Appendix A reflects the limited control authority in roll typical of a missile configured with differential stabilator for roll control as opposed to aileron.

The following control definitions and limits are applied:

a) Thrust (T) is a constant and is oriented along the x axis.

$$T = T_x = \text{constant}$$

δr

b) Rudder deflection (ζ) is defined as positive trailing edge left from the rear and is limited to

$$-15^\circ \leq \zeta \leq 15^\circ$$

c) Elevator deflection (η) is defined as positive trailing edge down (produces a nose down moment) and is limited to

δe

$$-15^\circ \leq \eta \leq 15^\circ$$

d) Aileron deflection (ξ) is defined as positive with trailing edge of the right aileron up (produces a positive (clockwise from the rear) roll) and is limited to

$$-15 \le \overset{\delta a}{\xi} \le 15^{\circ}$$

e) Left horizontal stabilizer deflection (η_L) is positive trailing edge down.

$$\eta_L = \eta + \xi$$

f) Right horizontal stabilizer deflection (η_R) is positive trailing edge down.

$$\eta_R = \eta - \xi$$

B. AERODYNAMIC COEFFICIENT BUILD UP

Aerodynamic forces and moments are built up from coefficient data in standard fashion using the following relations:

$$D = C_D \, \bar{q} \, S \qquad L = C_L \, \bar{q} \, S \qquad Y = C_y \, \bar{q} \, S$$

$$M_A = C_M \, \bar{q} S \bar{c} \qquad L_A = C_l \bar{q} S \bar{b} \qquad N_A = C_n \, \bar{q} \, Sb$$

1. Definition of Coefficients

Each coefficient is partitioned into two parts; a static term and a dynamic term as follows:

$$C_D = C_{D_{ST}} + C_{D_{DYN}}$$

$$C_L = C_{L_{ST}} + C_{L_{DYN}}$$

$$C_Y = C_{Y_{ST}} + C_{Y_{DYN}}$$

$$C_m = C_{m_{ST}} + C_{m_{DYN}}$$

$$C_l = C_{l_{ST}} + C_{l_{DYN}}$$

$$C_n = C_{n_{ST}} + C_{n_{DYN}}$$

2. Coefficient Build Up

The static terms are constructed from coefficient data stored in tables (Appendix A) as functions of two or three variables (either α, β, M, η, ζ, ξ) as follows:

$$C_{L_{basic}} = f\ (\alpha, \beta, M)$$

$$\Delta C_{L_{ST}}(\eta) = f\ (\alpha, \beta, \eta)$$

$$C_{D_{basic}} = f\ (\alpha, \beta, M)$$

$$\Delta C_{D_{ST}}(\eta) = f\ (\alpha, \beta, \eta)$$

$$\Delta C_{D_{ST}}(\xi) = f\ (\alpha, \beta, \xi)$$

$$\Delta C_{D_{ST}}(\zeta) = f\ (\alpha, \beta, \zeta)$$

$$C_{Y_{basic}} = f\ (\alpha, \beta)$$

$$\Delta C_{Y_{ST}}(\zeta) = f\ (\alpha, \beta, \zeta)$$

$$\Delta C_{Y_{ST}}(\xi) = f\ (\alpha, \beta, \xi)$$

$$C_{m_{basic}} = f\ (\alpha, \beta, M)$$

$$\Delta C_{m_{ST}}(\eta) = f\ (\alpha, \beta, \eta)$$

$$C_{n_{basic}} = f\ (\alpha, \beta)$$

$$\Delta C_{n_{ST}}(\zeta) = f\ (\alpha, \beta, \zeta)$$

$$\Delta C_{n_{ST}}(\xi) = f\ (\alpha, \beta, \xi)$$

η : elevator
ζ : rudder
ξ : aileron

$$C_{l_{basic}} = f\ (\alpha, \beta)$$

$$C_{l_{ST}}\ (\xi) = f\ (\alpha, \beta, \xi)$$

$$C_{l_{ST}}\ (\zeta) = f\ (\alpha, \beta, \zeta)$$

The static coefficients are formed as:

$$C_{L_{ST}} = C_{L_{basic}} + \Delta C_L\ (\eta)$$

$$C_{D_{ST}} = C_{D_{basic}} + \Delta C_{D_{ST}}(\eta) + \Delta C_{D_{ST}}(\xi) + \Delta C_{D_{ST}}(\zeta)$$

$$C_{Y_{ST}} = C_{Y_{basic}} + \Delta C_{Y_{ST}}(\zeta) + \Delta C_{Y_{ST}}(\xi)$$

$$C_{m_{ST}} = C_{m_{basic}} + \Delta C_{m_{ST}}(\eta)$$

$$C_{n_{ST}} = C_{n_{basic}} + \Delta C_{n_{ST}}(\xi) + \Delta C_{n_{ST}}(\zeta)$$

$$C_{l_{ST}} = C_{l_{basic}} + \Delta C_{l_{ST}}(\xi) + \Delta C_{l_{ST}}(\zeta)$$

The dynamic terms are constructed from dynamic coefficient data stored in tables (Appendix A) as a function of angle of attack and Mach number $f\ (\alpha, M)$. They are $C_{L_{\dot{\alpha}\pi}}$, C_{L_q}, $C_{D_{\dot{\alpha}}}$, C_{D_q}, $C_{Y_{\dot{\beta}}}$, C_{Y_r}, C_{Y_p}, $C_{m_{\dot{\alpha}}}$, C_{m_q}, $C_{n_{\dot{\beta}}}$, C_{n_r}, C_{n_p}, C_{l_r}, and C_{l_p}.

The dynamic coefficients are formed as:

$$C_{L_{DYN}} = \frac{\bar{c}}{2V_T}\left(C_{L_{\dot{\alpha}}}\dot{\alpha} + C_{L_q}\ q\right)$$

$$C_{D_{DYN}} = \frac{\bar{c}}{2V_T}\left(C_{D_{\dot{\alpha}}}\dot{\alpha} + C_{D_q}\ q\right)$$

$$C_{Y_{DYN}} = \frac{b}{2V_T}\left(C_{Y_r}\ r + C_{Y_p}\ p + C_{Y_{\dot{\beta}}}\ \dot{\beta}\right)$$

$$C_{m_{DYN}} = \frac{\bar{c}}{2V_T}\left(C_{m_{\dot{\alpha}}}\dot{\alpha} + C_{m_q} q\right)$$

$$C_{n_{DYN}} = \frac{b}{2V_T}\left(C_{n_{\dot{\beta}}}\dot{\beta} + C_{n_r} r + C_{n_p} p\right)$$

$$C_{l_{DYN}} = \frac{b}{2V_T}\left(C_{l_r} r + C_{l_p} p\right)$$

The total coefficient build up is summarized below.

$$C_L = C_{L_{basic}} + \Delta C_{L_{ST}}(\eta) + \frac{\bar{c}}{2V_T}\left(C_{L_{\dot{\alpha}}}\dot{\alpha} + C_{L_q} q\right)$$

$$C_D = C_{D_{basic}} + \Delta C_{D_{ST}}(\eta) + \Delta C_{D_{ST}}(\xi) + \Delta C_{D_{ST}}(\zeta) + \frac{\bar{c}}{2V_T}\left(C_{D_{\dot{\alpha}}}\dot{\alpha} + C_{D_q} q\right)$$

$$C_Y = C_{Y_{basic}} + \Delta C_{Y_{ST}}(\zeta) + \Delta C_{Y_{ST}}(\xi) + \frac{\bar{b}}{2V_T}\left(C_{Y_r} r + C_{Y_r} p + C_{Y_{\dot{\beta}}}\dot{\beta}\right)$$

$$C_m = C_{m_{basic}} + \Delta C_{m_{ST}}(\eta) + \frac{\bar{c}}{2V_T}\left(C_{m_{\dot{\alpha}}}\dot{\alpha} + C_{m_q} q\right)$$

$$C_n = C_{n_{basic}} + \Delta C_{n_{ST}}(\zeta) + \Delta C_{n_{ST}}(\xi) + \frac{\bar{b}}{2V_T}\left(C_{n_{\dot{\beta}}}\dot{\beta} + C_{n_r} r + C_{n_p} p\right)$$

$$C_l = C_{l_{basic}} + \Delta C_{l_{ST}}(\zeta) + \Delta C_{l_{ST}}(\xi) + \frac{b}{2V_T}\left(C_{l_r} r + C_{l_p} p\right)$$

C. MISSILE LINEARIZED EQUATIONS OF MOTION

The linearized equations of motion used to design the missile autopilot are presented in this section. The equations are linearized about the cruise flight condition.

1. Additional Assumptions for Linearized Equations

The additional assumptions required for linearized equations are as follows:

a) Derivatives are given in stability axes which are fixed for the missile low level cruise condition.

b) Standard small perturbation assumptions apply.

1) Perturbed angles are small.

2) Products of perturbed variables are neglected.

3) There is no coupling between longitudinal and lateral directional motions.

c) Thrust derivatives are neglected.

d) The steady state condition is chosen as low level straight and level cruise.

2. Linearized Equations Summarized

The linear equations of motion in state variable form are shown in Tables 2-1 and 2-2. The following coefficients are defined as used in Table 2-2.

$$A = \frac{I_{zz}I_{xz}}{I_{zz}I_{xx}-I_{xz}^2} \qquad B = \frac{I_{xx}}{I_{xz}}$$

$$C = \frac{I_{xx}I_{xz}}{I_{zz}I_{xx}-I_{xz}^2} \qquad D = \frac{I_{zz}}{I_{xz}}$$

3. Definition of Stability Derivatives

The dimensional aerodynamic stability derivatives used in the equations of motion are defined by the following relations.

a. Longitudinal Dimensional Stability Derivatives

$X_U = -\bar{q}_{SS}S(C_{D_U}+2C_{D_{SS}})/mU_{SS}$ 1/sec

$X_\alpha = \bar{q}_{SS}S(C_{L_{SS}}-C_{D_\alpha})/m$ ft/sec

$X_{\delta e}$ $X_\eta = -\bar{q}_{SS}SC_{D_\eta}/m$ ft/sec^2

$Z_U = -\bar{q}_{SS}S(C_{L_U}+2C_{L_{SS}})/mU_{SS}$ 1/sec

TABLE 2-1

Longitudinal Equations (Perturbed Variables) (11)

$$\begin{bmatrix} \dot{U} \\ \dot{\alpha} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} X_U & X_\alpha & 0 & -g\cos\gamma_{SS} \\ \frac{Z_w}{U_{SS}-Z_{\dot{\alpha}}} & \frac{Z_\alpha}{U_{SS}-Z_{\dot{\alpha}}} & \frac{U_{SS}+Z_q}{U_{SS}-Z_{\dot{\alpha}}} & \frac{-g\sin\gamma_{SS}}{U_{SS}-Z_{\dot{\alpha}}} \\ \frac{M_U+M_{\dot{\alpha}}Z_U}{U_{SS}-Z_{\dot{\alpha}}} & \frac{M_\alpha+M_{\dot{\alpha}}Z_\alpha}{U_{SS}-Z_{\dot{\alpha}}} & \frac{M_q+M_{\dot{\alpha}}(U_{SS}+Z_q)}{U_{SS}-Z_{\dot{\alpha}}} & \frac{-M_{\dot{\alpha}}g\sin\gamma_{SS}}{U_{SS}-Z_{\dot{\alpha}}} \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} U \\ \alpha \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} X_\eta \\ \frac{Z_\eta}{U_{SS}-Z_{\dot{\alpha}}} \\ \frac{M_\eta+M_{\dot{\alpha}}Z_\eta}{U_{SS}-Z_{\dot{\alpha}}} \\ 0 \end{bmatrix} \eta$$

TABLE 2-2

Lateral Directional Equations (Perturbed Variables) (12)

$$\begin{bmatrix} \dot{\beta} \\ \dot{\phi} \\ \dot{p} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \frac{Y_\beta}{U_{SS}} & \frac{g\cos\gamma_{SS}}{U_{SS}} & \frac{Y_p}{U_{SS}} & \frac{Y_r-U_{SS}}{U_{SS}} \\ 0 & 0 & 1 & 0 \\ A(N_\beta+BL_\beta) & 0 & A(N_p+BL_p) & A(N_r+BL_r) \\ C(L_\beta+DN_\beta) & 0 & C(L_p+DN_p) & C(L_r+DN_r) \end{bmatrix} \begin{bmatrix} \beta \\ \phi \\ p \\ r \end{bmatrix} + \begin{bmatrix} \frac{Y_\xi}{U_{SS}} & \frac{Y_\zeta}{U_{SS}} \\ 0 & 0 \\ A(N_\xi+BL_\xi) & A(N_\zeta+BL_\zeta) \\ C(L_\xi+DN_\xi) & C(L_\zeta+DN_\zeta) \end{bmatrix} \begin{bmatrix} \xi \\ \zeta \end{bmatrix}$$

$Z_\alpha = -\bar{q}_{SS}S(C_L + C_{D_{SS}})/m$ ft/sec^2

$Z_{\dot{\alpha}} = -\bar{q}_{SS}S\bar{c}C_{L_{\dot{\alpha}}}/2mU_{SS}$ ft/sec

$Z_q = -\bar{q}_{SS}S\bar{c}C_{L_q}/2mU_{SS}$ ft/sec

$Z_{\delta e}$ $Z_\eta = -\bar{q}_{SS}SC_{L_\eta}/m$ ft/sec

$M_U = \bar{q}_{SS}S\bar{c}(C_{M_U} + 2C_{M_{SS}})/I_{yy}U_{SS}$ 1/ft sec

$M_\alpha = \bar{q}_{SS}S\bar{c}C_{M_\alpha}/I_{yy}$ 1/sec^2

$M_{\dot{\alpha}} = \bar{q}_{SS}S\bar{c}^2C_{m_{\dot{\alpha}}}/2I_{yy}U_{SS}$ 1/sec

$M_q = \bar{q}_{SS}S\bar{c}^2C_{m_q}/2I_{yy}U_{SS}$ 1/sec

$M_{\delta e}$ $M_\eta = \bar{q}_{SS}S\bar{c}C_{m_\eta}/I_{yy}$ 1/sec^2

b. Lateral Directional Dimensional Stability Derivatives

$Y_\beta = \bar{q}_{SS}SC_{y_\beta}/m$ ft/sec^2

$Y_p = \bar{q}_{SS}SbC_{y_p}/2mU_{SS}$ ft/sec

$Y_r = \bar{q}_{SS}SbC_{y_r}/2mU_{SS}$ ft/sec

$Y_\xi = \bar{q}_{SS}SC_{y_\xi}/m$ $Y_{\delta a}$ ft/sec^2

$Y_\zeta = \bar{q}_{SS}SC_{y_\zeta}/m$ $Y_{\delta r}$ ft/sec^2

$L_\beta = \bar{q}_{SS}SbC_{l_\beta}/I_{xx}$ 1/sec^2

$L_p = \bar{q}_{SS}Sb^2C_{l_p}/2I_{xx}U_{SS}$ 1/sec

$L_r = \bar{q}_{SS}Sb^2C_{l_r}/2I_{xx}U_{SS}$ 1/sec

$L\delta a$ $L_\xi = \bar{q}_{SS} S b C_{l_\xi}/I_{xx}$ 1/sec^2

$L\delta r$ $L_\zeta = \bar{q}_{SS} S b C_{l_\zeta}/I_{xx}$ 1/sec^2

$N_\beta = \bar{q}_{SS} S b C_{n_\beta}/I_{zz}$ 1/sec^2

$N_p = \bar{q}_{SS} S b^2 C_{n_p}/2 I_{zz} U_{SS}$ 1/sec

$N_r = \bar{q}_{SS} S b^2 C_{n_r}/2 I_{zz} U_{SS}$ 1/sec

$N\delta a$ $N_\xi = \bar{q}_{SS} S b C_{n_\xi}/I_{zz}$ 1/sec^2

$N\delta r$ $N_\zeta = \bar{q}_{SS} S b C_{n_\zeta}/I_{zz}$ 1/sec^2

4. Trim Equations

For straight and level flight at constant velocity the following variables are all zero: $\dot{U}=\dot{V}=\dot{W}=\dot{P}=\dot{Q}=\dot{R}=\dot{\theta}=\dot{\Psi}=\dot{\Phi}=\dot{Z}_E=0$ $Q_{SS}=P_{SS}=R_{SS}=\Phi_{SS}=L_{A_{SS}}=M_{A_{SS}}=N_{A_{SS}}=Y_{SS}=\gamma_{SS}=\beta_{SS}=V_{SS}=W_{SS}=\xi_{SS}=\zeta_{SS}=0$

The trim equations reduce to:

$$T\sin\alpha_{SS} = mg-(C_{L_o}+C_{L_\alpha}\alpha_{SS}+C_{L_\eta}\eta_{SS})\bar{q}_{SS}S$$

$$T\cos\alpha_{SS} = (C_{D_o}+C_{D_\alpha}\alpha_{SS}+C_{D_\eta}\eta_{SS})\bar{q}_{SS}S$$

$$0 = (C_{m_o}+C_{m_\alpha}\alpha_{SS}+C_{m_\eta}\eta_{SS})\bar{q}_{SS}S\bar{c}$$

III. DEVELOPMENT AND SIMULATION OF THE MISSILE AUTOPILOT

The missile is assumed to be equipped with an autopilot capable of providing closed loop control which consists of the following:

a) normal acceleration (n_z)

b) lateral acceleration (n_y)

c) bank angle (ϕ).

In addition, an outer closed loop control, which serves as the outer autopilot, is as follows:

a) altitude (H)

b) vertical flight path angle (γ)

These two outer loops are employed as required during certain phases of the attack mission.

It is assumed that the missile possesses accelerometer sensors in the y and z body axes located at the missile center of gravity, rate gyros and rate integrating gyros about the x, y, and z axes, and a radar altimeter. Sensor noise is neglected in this simulation.

A. AUTOPILOT INNER LOOP REQUIREMENTS AND DESIGNS

1. Description of the Autopilot Inner Loops

The autopilot is assumed to employ three inner loops as depicted in Table 3-1.

TABLE 3-1

Autopilot Inner Loop Description

LOOP	COMMANDED VARIABLE	CONTROL	CONSTRAINTS
1 Normal Acceleration Command	n_z (normal acceleration)	η Elevator	$-15^\circ \leq \eta \leq 15^\circ$ $-2 \leq N_z \leq 4$
2 Bank Angle Command	ϕ (Bank Angle)	ξ Aileron	$-15^\circ \leq \xi \leq 15^\circ$ $\phi \leq 60^\circ$* $p \leq 50,100,200^\circ/\text{sec}$
3 Turn Coordinator	n_y (Lateral Acceleration)	ζ Rudder	$-15^\circ \leq \zeta \leq 15^\circ$ $N_y = 0$

* Applies in certain mission phases only

2. Normal Acceleration Command System

The purpose of normal acceleration command (NAC) system is to provide a vertical load factor (n_z) response to a commanded load factor (n_{z_c}). An accelerometer is used to provide the primary feedback and a rate gyro is used to provide inner loop pitch rate feedback for improved damping.

a. Block Diagram

The block diagram of the normal acceleration command autopilot is shown in Figure 3-1. Limiter a allows the commanded acceleration to a range from -2.0 to +4.0 g's. Limiter b allows the elevator control to vary from -15 degrees to +15 degrees.

b. Assumptions

1) The rate gyro and accelerometer dynamic lags are negligible.

2) The accelerometer is mounted at the center of gravity. Therefore the moment arm is zero and the feedback load factor is totally n_z. (C=0)

3) The fix servo can be represented by a first order lag.

4) The missile dynamics can be represented by a short period approximation.

5) Commanded normal acceleration is limited from -2.0 to +4.0 g's.

c. Design

The following transfer function was developed from equation (11):

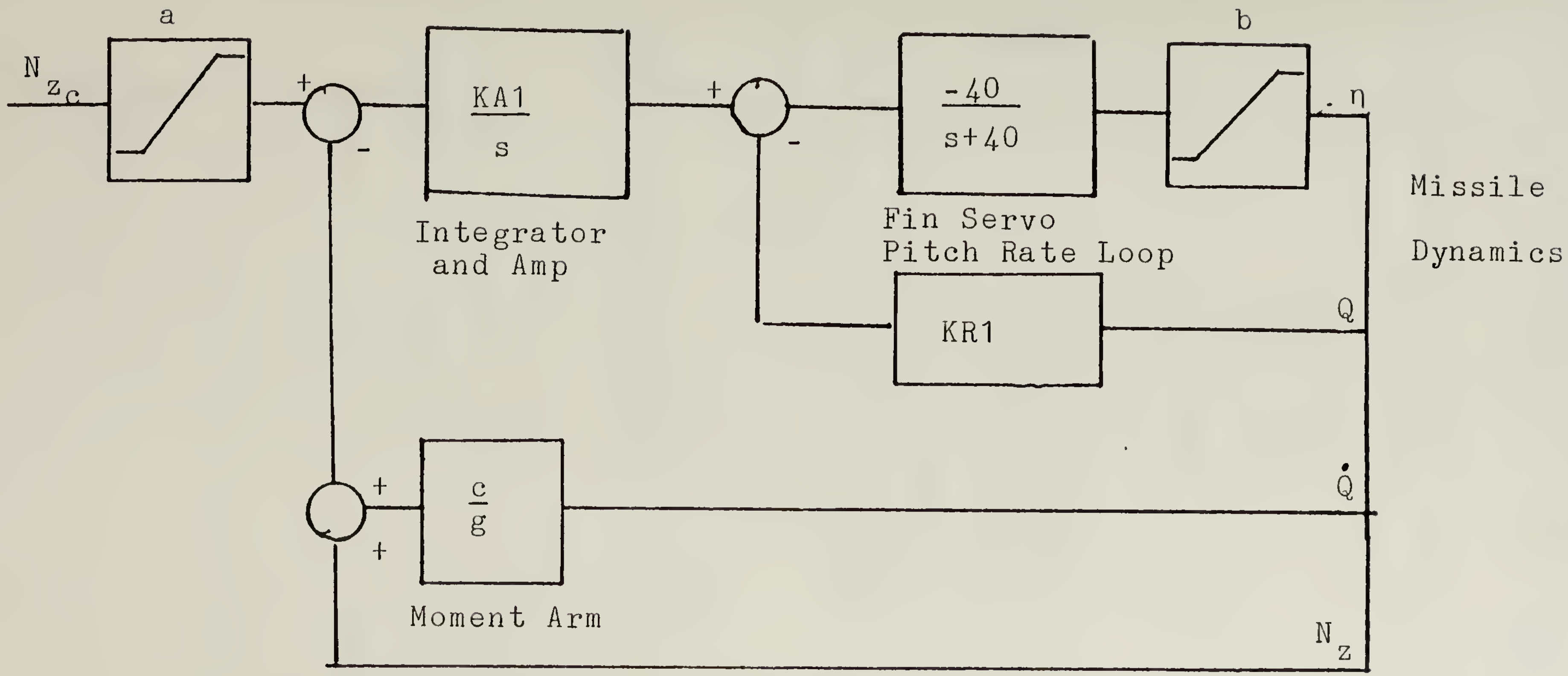


Figure 3-1 Normal Acceleration Command Autopilot Description

$$\frac{Q(s)}{\eta(s)} = \frac{V_T M_\eta + Z_\eta M_{\dot{\alpha}})s + (M_\alpha Z_\eta - Z_\alpha M_\eta)}{V_T\{s^2 - (M_q + \frac{Z_\alpha}{V_T} + M_{\dot{\alpha}})\ s + (\frac{Z_{\dot{\alpha}} M_q}{V_T} - M_\alpha)\ \}}$$

From this transfer function and equation (10a)

$$n_z = \frac{V_T}{g}(Q - \dot{\alpha})$$

the following θ to n_z transfer function was obtained.

$$\frac{N_z(s)}{Q(s)} = \frac{V_T}{g}\ \frac{-Z_\eta s^2 + (M_q Z_\eta + Z_\eta M_{\dot{\alpha}})s + (M_\alpha Z_\eta - Z_\alpha M_\eta)}{(V_T M_\eta + Z_\eta M_{\dot{\alpha}})s + (M_\alpha Z_\eta - Z_\alpha M_\eta)}$$

Utilizing the characteristics listed in Appendix A for this cruise missile at 0.75 Mach number, the above transfer functions become

$$\frac{Q(s)}{\eta(s)} = \frac{-26.99(s+1.009)}{s^2+1.289s+27.13} \quad \text{and} \quad \frac{N_z(s)}{Q(s)} = \frac{-0.08(s^2+0.1985s-328.9)}{(s+1.009)}$$

Evaluating the characteristic polynomial of the $Q(s)/\eta(s)$ transfer function yields the natural frequency of 0.829 Hz and a damping ratio of 0.1237. The resulting block diagram for the normal acceleration command inner loop autopilot for analysis purposes is shown in Figure 3-2.

(1) Root Locus Evaluation.

(a) Pitch Rate Loop. The transfer function for the pitch rate loop is:

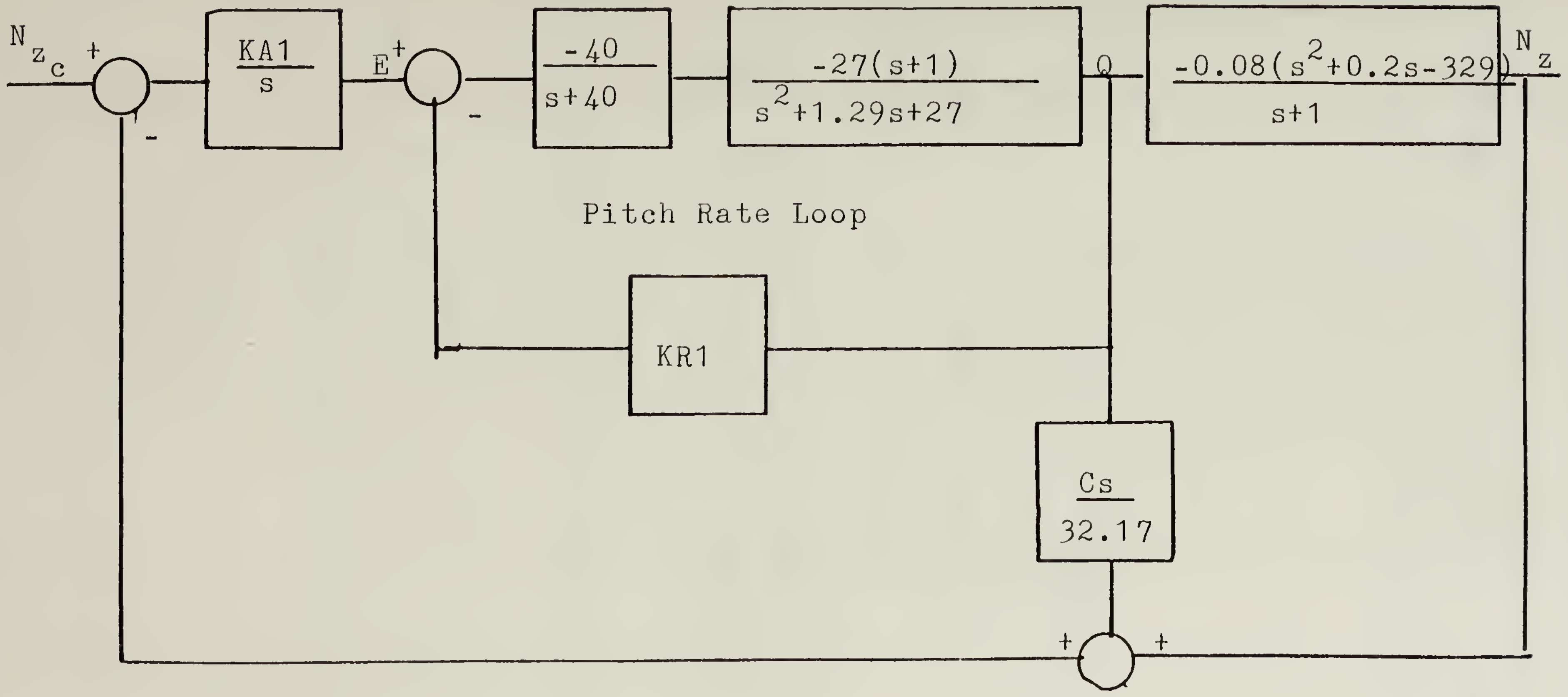


Figure 3-2 Normal Acceleration Command Autopilot Block Diagram (Analysis)

$$\frac{Q(s)}{E(s)} = \frac{1080\ (s+1)}{(s^3+41.29s^2+(78.7+1080KR1)s+(1084+1080KR1)}$$

Appendix C contains the root locus plot of the pitch rate loop for ranging KR1. A KR1 of 0.28 is chosen which yields the following characteristics:

$s = -5.600 \pm 3.844\, j$

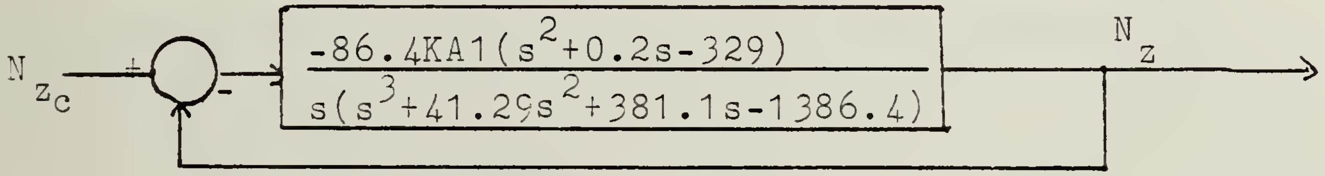
$\phi = 55.53^\circ$

$\zeta = 0.82$

$\omega_n = 1.08\ H_z$

(b) Normal Acceleration Command Loop.

Using a KR1 of 0.28 in the pitch rate loop, and locating the acceleration at the missile center of mass (C=0), the normal acceleration command loop becomes:


N_{z_c}
+
-
$\frac{-86.4KA1(s^2+0.2s-329)}{s(s^3+41.29s^2+381.1s-1386.4)}$
N_z

$$\frac{N_z(s)}{N_{z_c}(s)} = \frac{-86.4KA1(s^2+0.2s-329)}{s(s^3+41.29s+381.1s-1386.4)-86.4KA1(s^2+0.2s-329)}$$

Appendix C contains the root locus plot of the normal acceleration command system for varying KA1. A KA1 of 0.05 is chosen which yields the following characteristics:

$s = -1.981 \pm 3.317\, j$

$\phi = 30.85^\circ$

$\zeta = 0.513$

$\omega_n = 0.615H_z$

With a KR1 of 0.28 and a KA1 of 0.05 the system transfer function relating n_{z_c} to n_z is:

$$\frac{N_z(s)}{N_{z_c}(s)} = \frac{-4.32(s^2-0.2s-329)}{s^4+41.29s^3+376.78s^2-1387.26s-1421.28}$$

The normal acceleration command autopilot has zero steady state error for a step input as it is a type 1 system. The system response to a 1g commanded load factor is shown in Figure 3-3.

3. Bank Angle Command System

The purpose of the bank angle command (BAC) autopilot is to command missile bank angle. Limits are applied to commanded roll rate and in certain mission phases commanded bank angle. A rate integrating gyro feeds back bank angle and a roll rate gyro provides feedback as a roll rate damper.

a. Block Diagram

The bank angle command autopilot is presented in block diagram in Figure 3-4. Limiter a allows the commanded bank angle to vary from 0 to 60 degrees and is active in certain flight phases. Limiter b limits the roll rate to either 50, 100, or 200 degrees/second. Limiter c limits aileron deflections to range from -15 to +15 degrees.

b. Assumptions

1) The rate gyro and displacement dynamic lags are negligible.

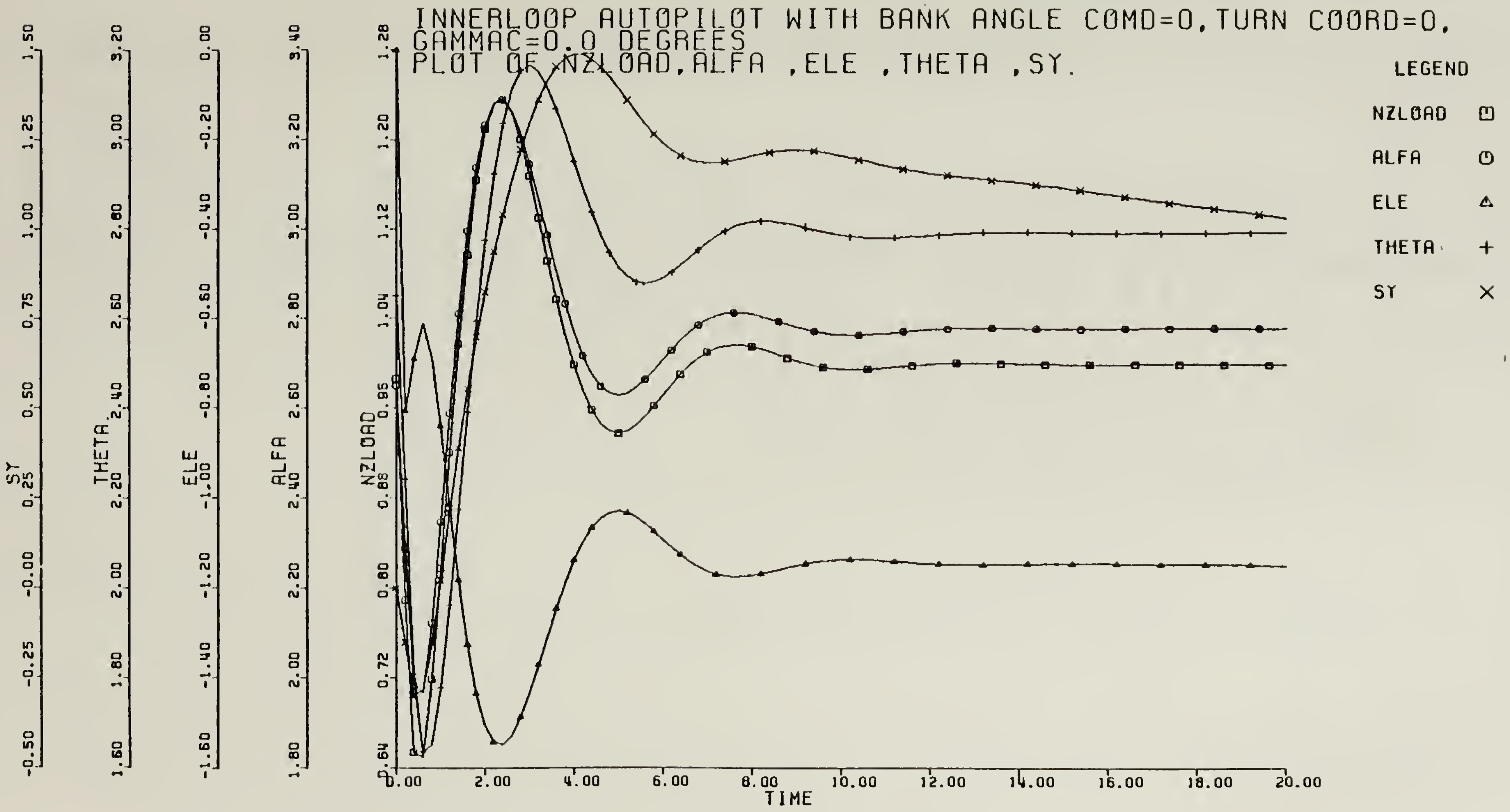


Figure 3-3 NAC Autopilot Response to 1g Commanded Load Factor

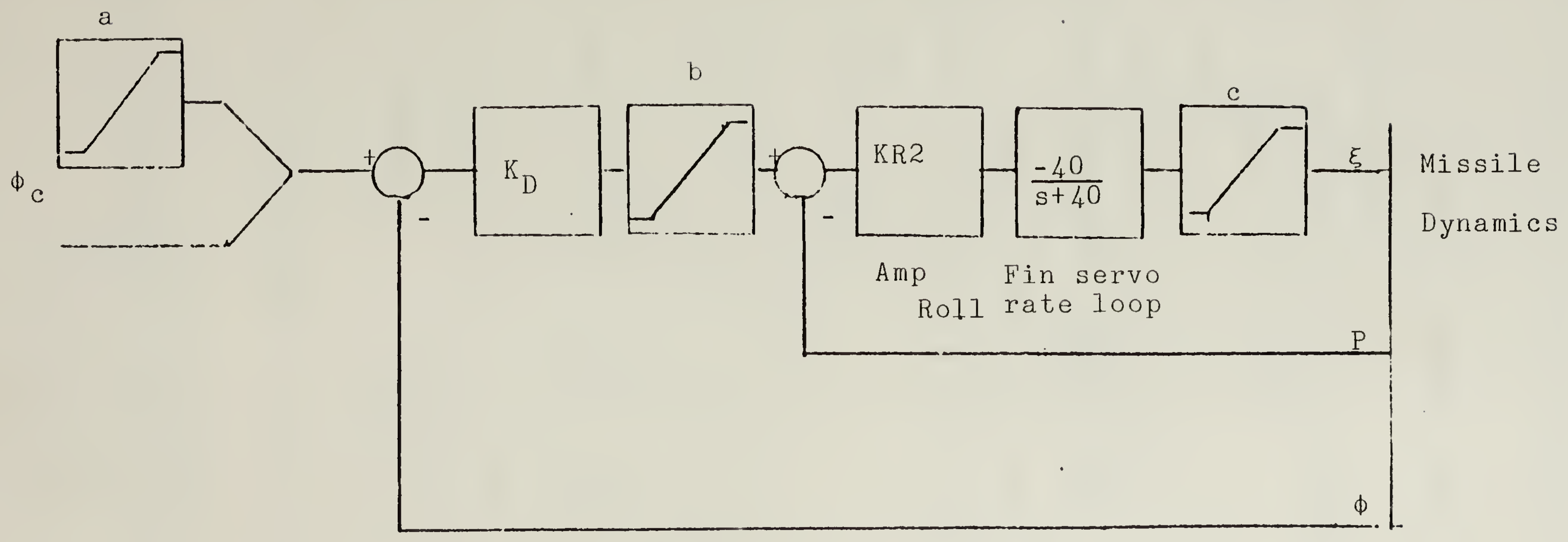


Figure 3-4 BANK ANGLE COMMAND AUTOPILOT DESCRIPTION

2) The fin servo can be represented by a first order lag.

3) The missile dynamics can be represented by a roll mode approximation.

4) There are limits on commanded bank angle and commanded roll rate as noted above.

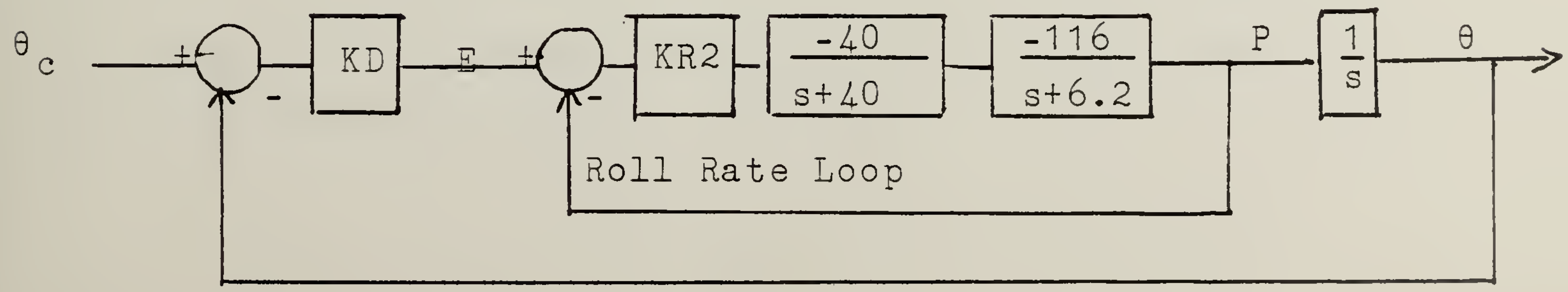
c. Design

Equation (12) can be written to find the lateral transfer functions $\frac{\beta(s)}{\zeta(s)}$, $\frac{\phi(s)}{\zeta(s)}$, and $\frac{\psi(s)}{\zeta(s)}$, where $\delta = \xi$ or ζ. By allowing a roll approximation the transfer function relating aileron and bank angle becomes:

$$\frac{\phi(s)}{\xi(s)} = \frac{L_{\xi}}{s(s-L_p)}$$

The root at the origin indicates the missile does not have bank angle stability without autopilot stabilization. Evaluation of the transfer function coefficients results in the transfer functions $\frac{\phi(s)}{\xi(s)} = \frac{-116}{s(s+6.2)}$ and $\frac{p(s)}{\xi} = \frac{-116}{s+6.2}$. The maximum missile roll rate can be approximated by $P_{max} = \left| \frac{L_{\xi}\xi_{max}}{L_p} \right| = \frac{(116)(15)}{6.2} = 280.6$ degrees/second.

The block diagram of the bank angle command system is:



(1) Root Locus Evaluation.

(a) Roll Rate Loop. The transfer function for the roll rate loop is:

$$\frac{P(s)}{E(s)} = \frac{4640\ KR2}{s^2+46.2s+248+4640KR2}$$

Appendix C contains the root locus plot of the roll rate loop for varying KR2. A gain KR2 of 0.10 yields the following characteristics.

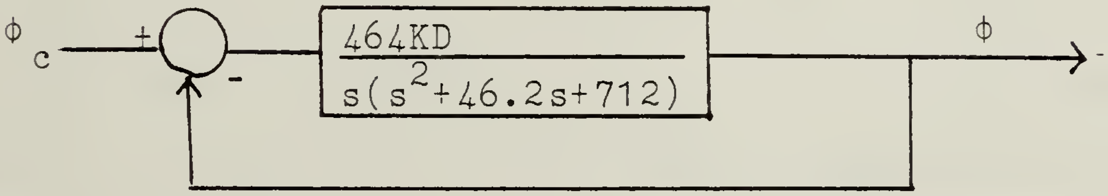
$s = -23.10 \pm 13.36\ s$

$\phi = 59.96^\circ$

$\zeta = 0.8656$

$\omega_n = 4.247H_Z$

(b) Bank Angle Command Loop. With a KR2 of 0.10 the bank angle command loop becomes:



The transfer function is:

$$\frac{\phi(s)}{\phi_c(s)} = \frac{464KD}{s^3+46.2s^2+712s+464KD}$$

The root locus plot is shown in Appendix C for varying KD. Choosing a KD gain of 10.8 yields the following characteristics:

$s = -9.98 \pm 9.58j$

$\phi = 45.056^{\circ}$

$\zeta = 0.718$

$\omega_n = 2.19\ H_Z$

Using gains of 0.10 for the inner loop and 10.8 for the outer loop of the bank angle command system, the system transfer function G(s) becomes

$$\frac{\phi(s)}{\phi_c(s)} = \frac{5011.2}{s^3+46.2s^2+712s+5011.2}$$

and the system is a type 1 system for a step input. The transient reponse is demonstrated in Figures 3-5 and 3-6 for a commanded bank angle of 60 degrees.

4. Turn Coordinator

The turn coordinator (TC) is a lateral autopilot which provides a body directional load factor, n_y, to a commanded load factor, n_{y_c}. Like the normal acceleration command autopilot it employs an inner loop yaw rate damper. The outer loop uses unity accelerometer feedback and has the capability of moment arm feedback if the accelerometer is located at a different position than the missile center of mass.

a. Block Diagram

The block diagram representing the turn coordinator autopilot is shown in Figure 3-7. Limiter a limits the rudder deflection (ζ) from -15 to +15 degrees.

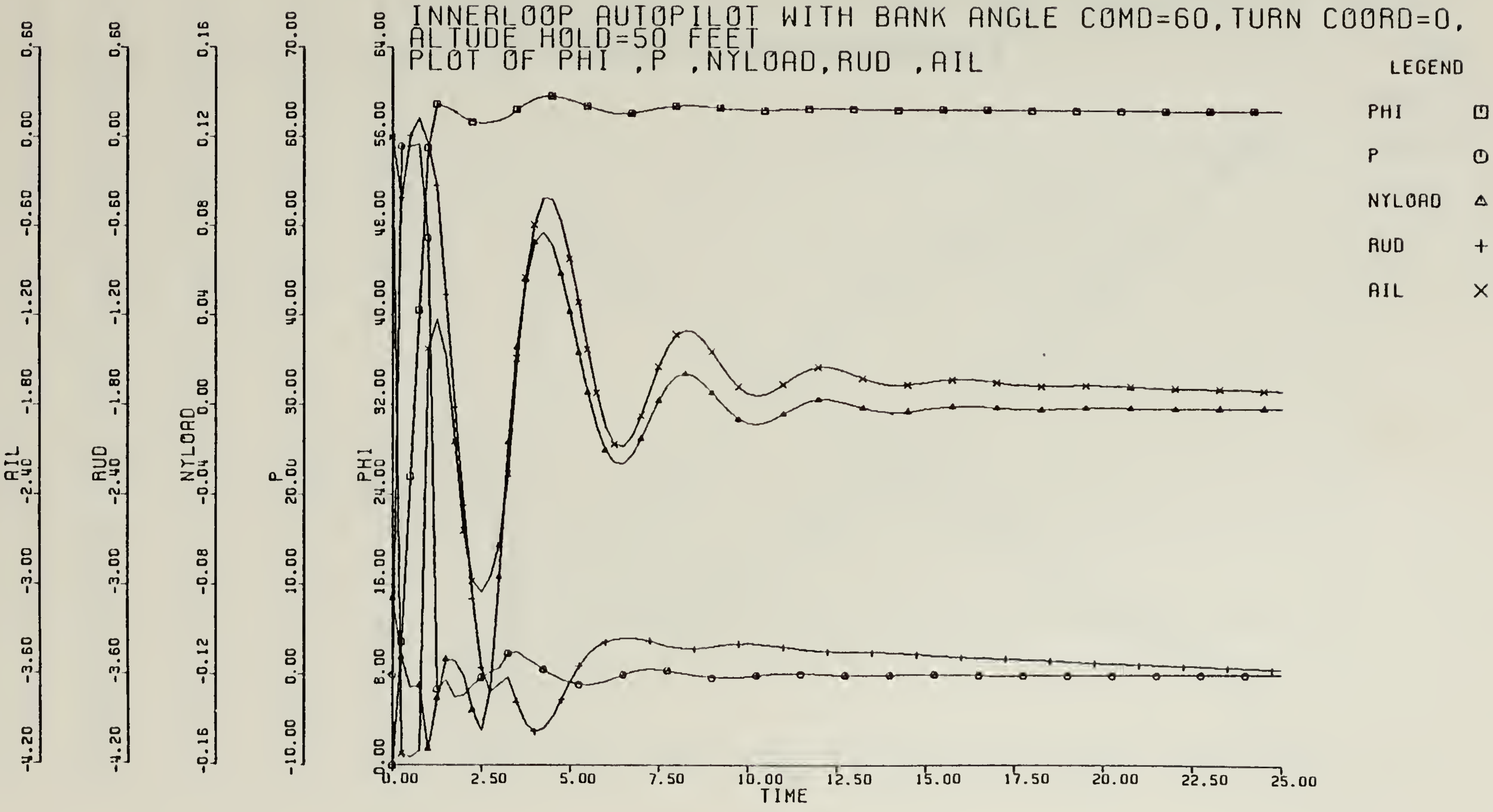


Figure 3-5 BAC Autopilot Response to 60° Commanded Bank Angle (PHI Response)

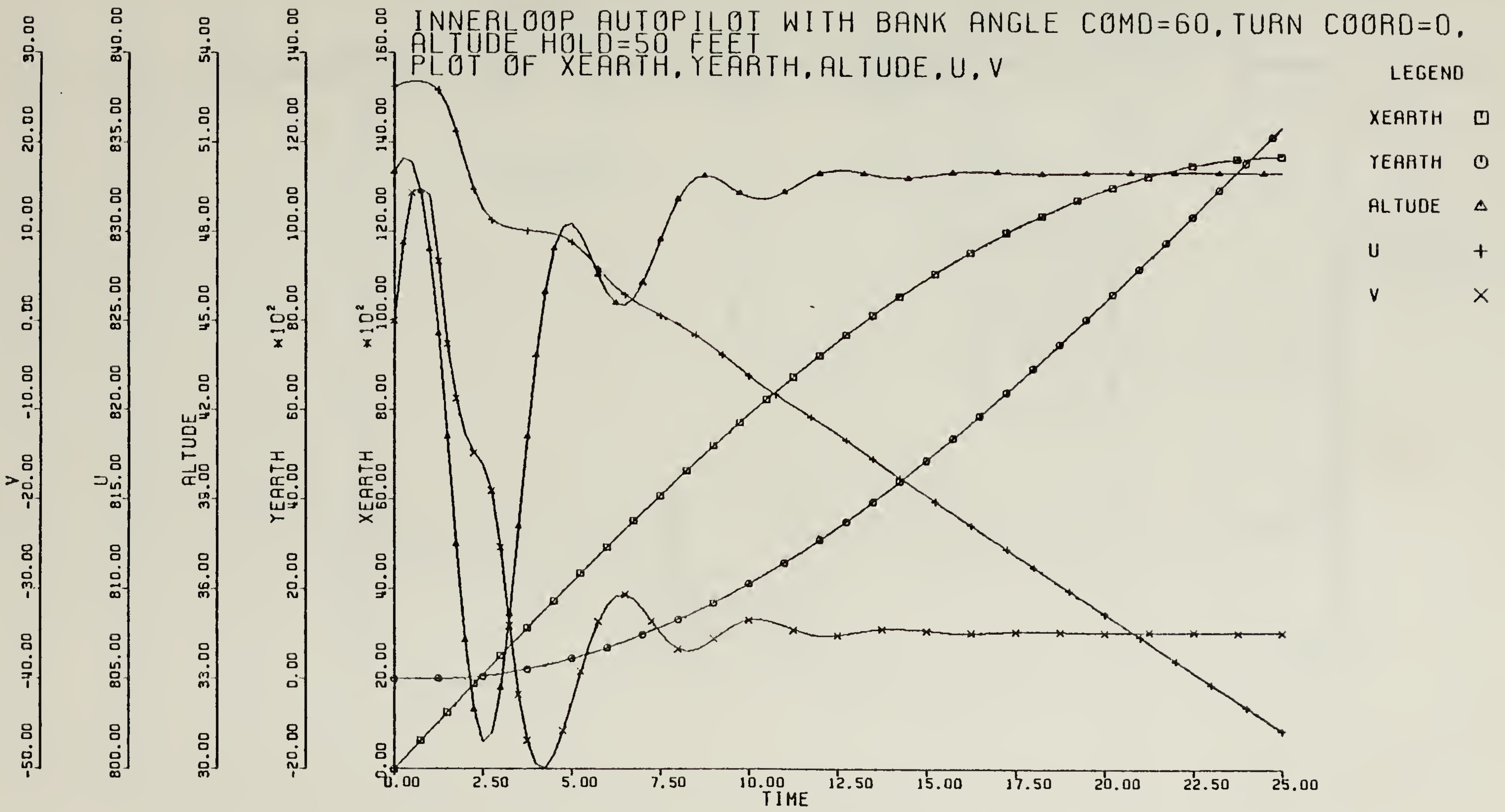


Figure 3-6 BAC Autopilot Response to 60° Commanded Bank Angle (Altitude Response)

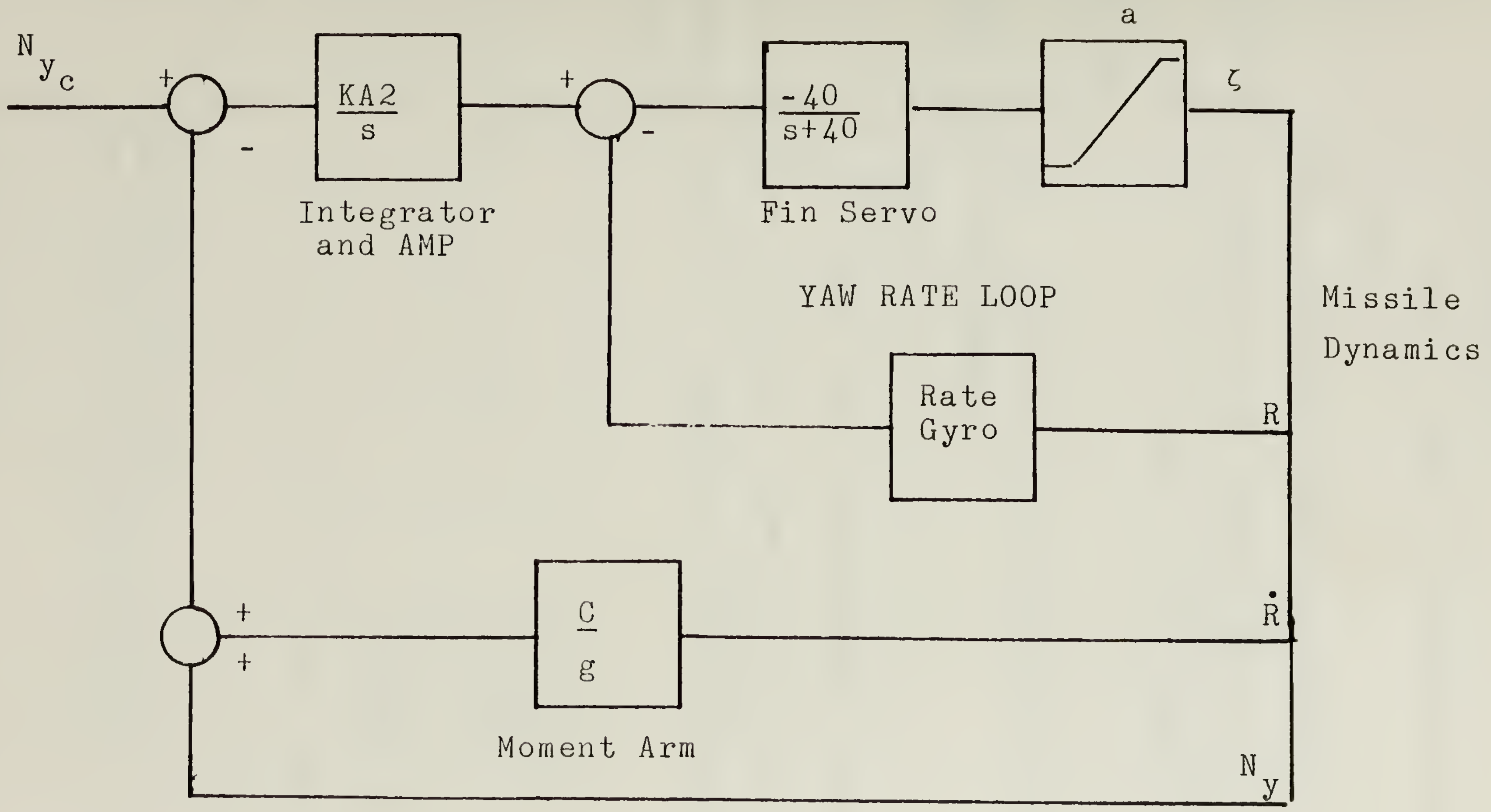


Figure 3-7 Turn Coordinator Autopilot Description

b. Assumptions

1) The rate gyro and accelerometer dynamic lags are negligible.

2) An accelerometer is mounted at the center of gravity. Therefore the moment arm is zero. C=0

3) The fin servo can be represented by a first order lag.

4) The missile dynamics can be represented by a dutch roll approximation.

c. Design

The dutch roll approximation involves side slip angle β, and yaw angle Ψ. Equation (12) with ϕ neglected (assuming a small C_{l_β} results in the following set of equations:

$$\left[\begin{array}{c|c} sV_T - Y_\beta & s(V_T - Y_r) \\ \hline -N_\beta & s^2 - sN_r \end{array}\right] \begin{bmatrix} \dfrac{\beta(s)}{\zeta(s)} \\ \dfrac{\psi(s)}{\zeta(s)} \end{bmatrix} = \begin{bmatrix} Y_\zeta \\ N_\zeta \end{bmatrix}$$

The following transfer functions can be extracted:

$$\frac{\beta(s)}{\zeta(s)} = \frac{Y_\zeta s + (Y_r N_\zeta - V_T N_\zeta - Y_\zeta N_r)}{V_T s^2 - (Y_\beta + V_T N_r)s + (Y_\beta N_r + V_T N_\beta - Y_r N_\beta)}$$

$$\frac{\Psi(s)}{\zeta(s)} = \frac{V_T N_\zeta s + (Y_\zeta N_\beta - Y_\beta N_\zeta)}{s\{\, V_T s^2 - (Y_\beta + V_T N_r)s + (Y_\beta N_r + V_T N_\beta - Y_r N_\beta)\,\}}$$

$$\frac{R(s)}{\zeta(s)} = \frac{V_T N_\zeta s+(Y_\zeta N_\beta - Y_\beta N_{\cancel{\beta}\,\zeta})}{V_T s^2 - Y_\beta + V_T N_r)s+(Y_\beta N_r + V_T N_\beta - Y_r N_\beta)}$$

Using the equation (10b) in Chapter I the transfer function for yaw rate to n_y is

$$\frac{N_y(s)}{R(s)} = \frac{V_T}{g}\;\frac{Y_\zeta s^2+(Y_r N_\zeta - Y_\zeta N_r)s+(Y_\zeta N_\beta - Y_\beta N_\zeta)}{V_T N_\zeta s+(Y_\zeta N_\beta - Y_\beta N_\zeta)}$$

Substituting coefficient data obtained from Appendix A results in the transfer functions as:

$$\frac{R(s)}{\zeta(s)} = \frac{-14.5(s+0.11)}{s^2+0.245s+14.5}$$

$$\frac{N_y(s)}{R(s)} = \frac{-0.14(s^2-0.01s-20.9)}{s+0.11}$$

The resulting turn coordinator block diagram for analysis purposes is given in Figure 3-8.

(1) Root Locus Evaluation.

(a) Yaw Rate Loop. The loop transfer function is

$$\frac{R(s)}{E(s)} = \frac{580(s+0.11)}{s^3+40.25s^2+(24.3+580KR3)s+(580+63.8KR3)}$$

Appendix C shows the root locus plot of the yaw rate loop for varying KR3. Selecting a gain KR3 of 0.40 results in the following characteristics:

$s = -3.581 \pm 2.339j$

$\phi = 56.85^\circ$

$\zeta = 0.8372$

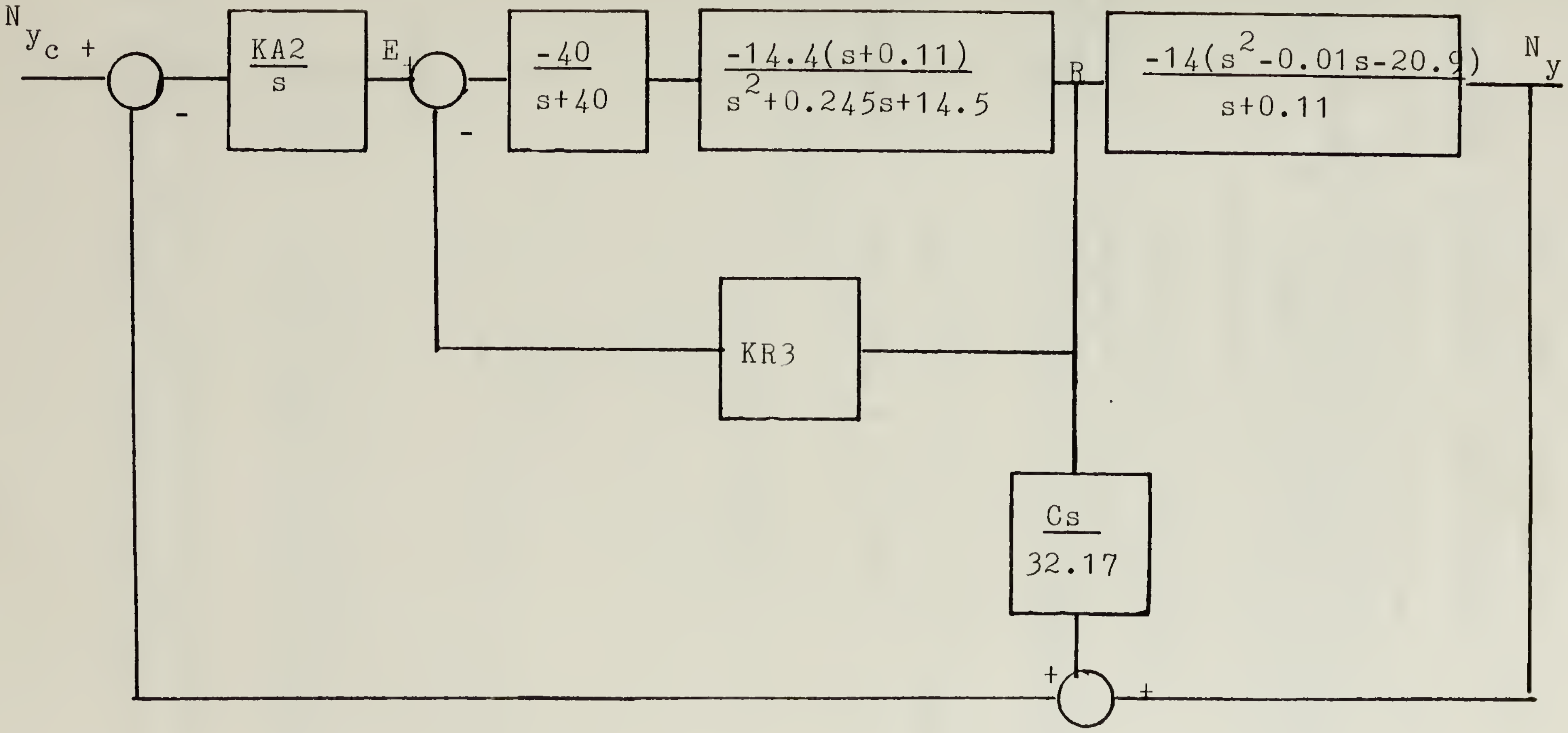
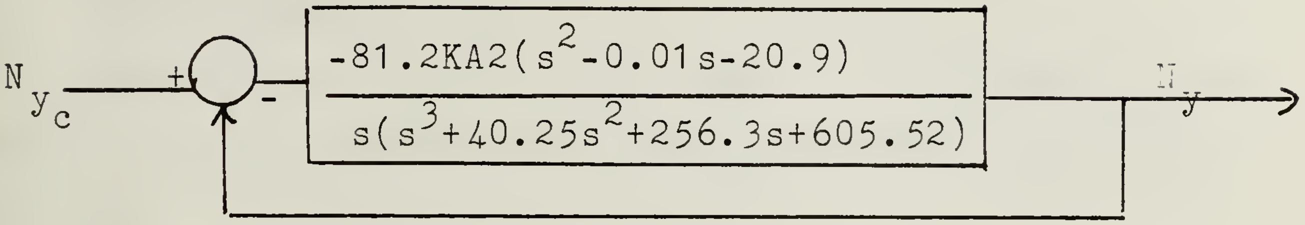


Figure 3-8 Turn Coordinator Autopilot Block Diagram (Analysis)

$$\omega_n = 0.6807 H_z$$

$$\phi = 56.85 \text{ degrees}$$

(b) Turn Coordinator Loop. With a KR3 of 0.40 the turn coordinator loop becomes:


N_{y_c}
+
-
$\frac{-81.2KA2(s^2-0.01s-20.9)}{s(s^3+40.25s^2+256.3s+605.52)}$
N_y

The transfer function is:

$$\frac{N_y(s)}{N_{y_c}(s)} = \frac{-81.2KA2(s^2-0.01s-20.9)}{s^4+40.25s^3+(244.7-81.2KA2)s^2+(604.2+81.2KA2)s + 1697KA2}$$

The root locus plot for varying KA2 is shown in Appendix C. Selecting a gain KA2 of 0.25 yields characteristics as follows:

$$s = -2.206 \pm 2.807j$$

$$\phi = 38.16^o$$

$$\zeta = 0.618$$

$$\omega_n = 0.5682Hz$$

The turn coordinator system transfer function G(s) becomes:

$$\frac{N_y(s)}{N_{y_c}(s)} = \frac{-32.48(s^2-0.01s-20.9)}{s^4+40.25s^3+212.2s^2+604.5s+678.8}$$

The system is type 1 and therefore has zero steady state error to a step input. Figure 2-5a shows the response

of the turn coordinator for a step aileron input. Note that an n_{y_c} of zero results in a coordinated turn.

B. AUTOPILOT OUTER LOOP REQUIREMENTS AND DESIGNS

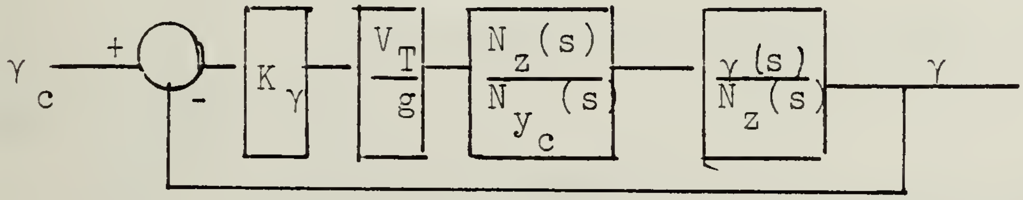
1. Description

The outer loop auto pilot has two functional loops consisting of an altitude hold and a vertical flight path angle hold.

2. Vertical Flight Path Angle System

The purpose of the vertical flight path angle hold loop or gamma command loop is to provide missile reponse to a command of 8.6 degrees during a specified phase in the terminal profile.

a. Block Diagram

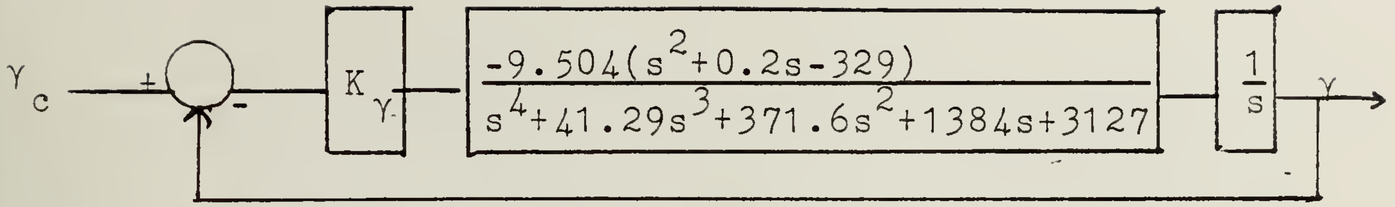


b. Assumption

1) Bank angle is zero.

c. Design

Starting with equation (10a) $n_z = \frac{V_T}{g}(Q-\dot{\alpha}) = \frac{V_T}{g}\dot{\gamma}$ the transfer function $\frac{\gamma(s)}{N_z(s)} = \frac{g}{V_T(s)}$ can be derived. Using the inner loop design previously for load factor the vertical flight path angle block diagram becomes:



The transfer function $\frac{\gamma(s)}{\gamma_c(s)}$ is:

$$\frac{\gamma(s)}{\gamma_c(s)} = \frac{-9.504K\ (s^2+0.2s-329)}{s^5+41.29s^4+37.6s^3+(1384-9.504K\ )s^2+(3127-1.9K_\gamma)s+3127K_\gamma}$$

(1) Root-Locus Evaluation. Appendix C shows the root locus plot of the vertical flight path angle loop for varying gain K_γ. A gain K_γ of 1.0 yields the following characteristics:

$s = 1.2725 \pm 2.5407j$

$\phi = 26.6^\circ$

$\zeta = 0.4478$

$\omega_n = 0.45H_Z$

The system transfer function G(s) with a gain of 1.0 becomes:

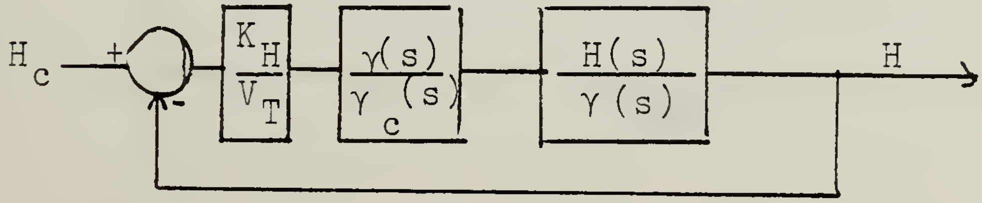
$$\frac{\gamma(s)}{\gamma_c\ (s)} = \frac{-9.504(s^2+0.2s-329)}{s^5+41.29s^4+371.6s^3+1374.5s^2+3125.1s+3127}$$

Figure 3-9 depicts the system response to a commanded vertical flight path angle of 8.6 degrees.

3. Altitude Hold System

The purpose of the altitude hold autopilot is to hold altitude at 50 feet during specified flight phases.

a. Block Diagram



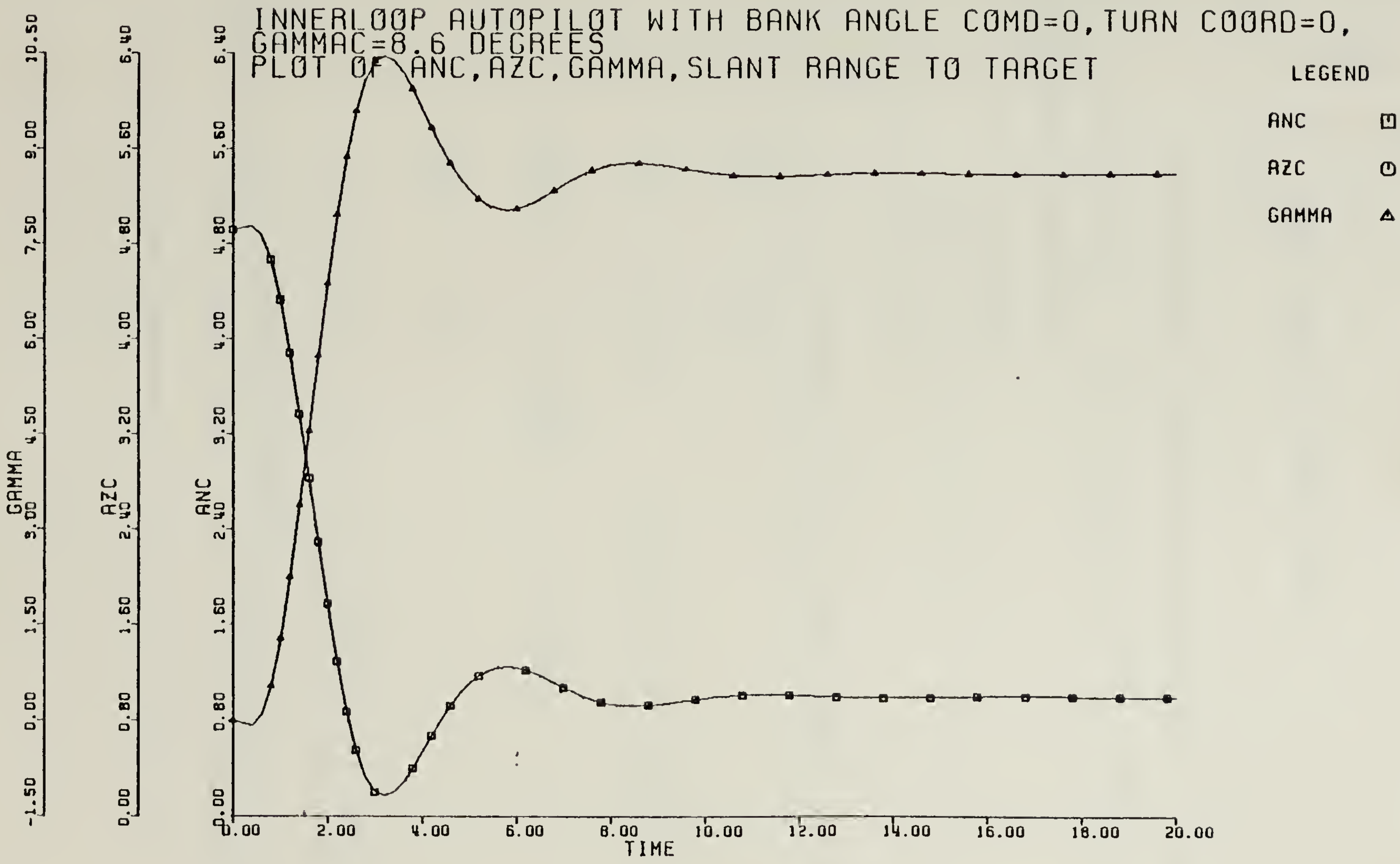


Figure 3-9 System Response to Commanded 8.6° Vertical Flight Path Angle

b. Assumptions

1) Vertical rate of climb (or desent) subtends a small angle (γ is less than 20°), therefore $H = V_T \sin\gamma = V_T\gamma$.

2) Bank angle equals zero.

c. Design

Let altitude command and altitude be designated H_C and H respectfully. The design is based upon the following two relations:

$$H = K_H(H_c - H)$$

$$\gamma_c = \frac{K_H}{V_T}(H_c - H)$$

From the vertical flight path angle development,

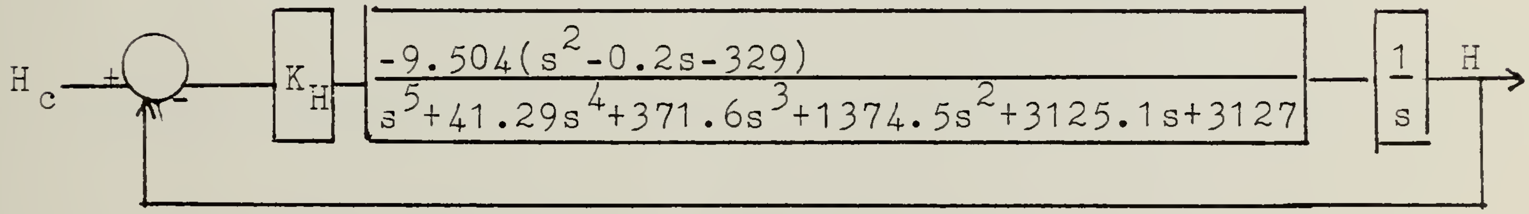
$$\frac{\gamma(s)}{N_z(s)} = \frac{g}{V_T s}$$

$$sH(s) = V_T\gamma(s) \qquad \text{(Divide both sides by } a_n(s))$$

$$\frac{sH(s)}{N_z(s)} = V_T \frac{\gamma(s)}{N_z(s)} = V_T \frac{g}{V_T s}$$

$$\frac{H(s)}{\gamma(s)} = \frac{V_T}{s}$$

The altitude hold block diagram becomes:


H_c
+
-
K_H
$\frac{-9.504(s^2-0.2s-329)}{s^5+41.29s^4+371.6s^3+1374.5s^2+3125.1s+3127}$
$\frac{1}{s}$
H

The transfer function $H(s)/H_c(s)$ is:

$$\frac{H(s)}{H_c(s)} = \frac{-9.504KH(s^2+0.2s-329)}{s^6+41.29s^5+371.6s^4+1374.5s^3+(3125.1-9.504KH)s^2+(3127-1.9KH)s+3127KH}$$

(1) Root Locus Evaluation. Appendix C contains the root locus plot of the altitude hold loop for a varying gain KH. Again KH of 0.3 results in characteristics:

$s = -1.4045 \pm 2.424j$

$\phi = 30.08^\circ$

$\zeta = 0.501$

$\omega_n = 0.445$ Hz

The altitude hold loop transfer function G(s) with KH of 0.3 is:

$$\frac{H(s)}{H_C(s)} = \frac{2.8512(s^2+0.2s-329)}{s^6+41.29s^5+371.6s^4+1374.5s^3+3122.25s^2+3126.4s+938.1}$$

and Figure 3-10 shows the response to a γ_c of 50 feet.

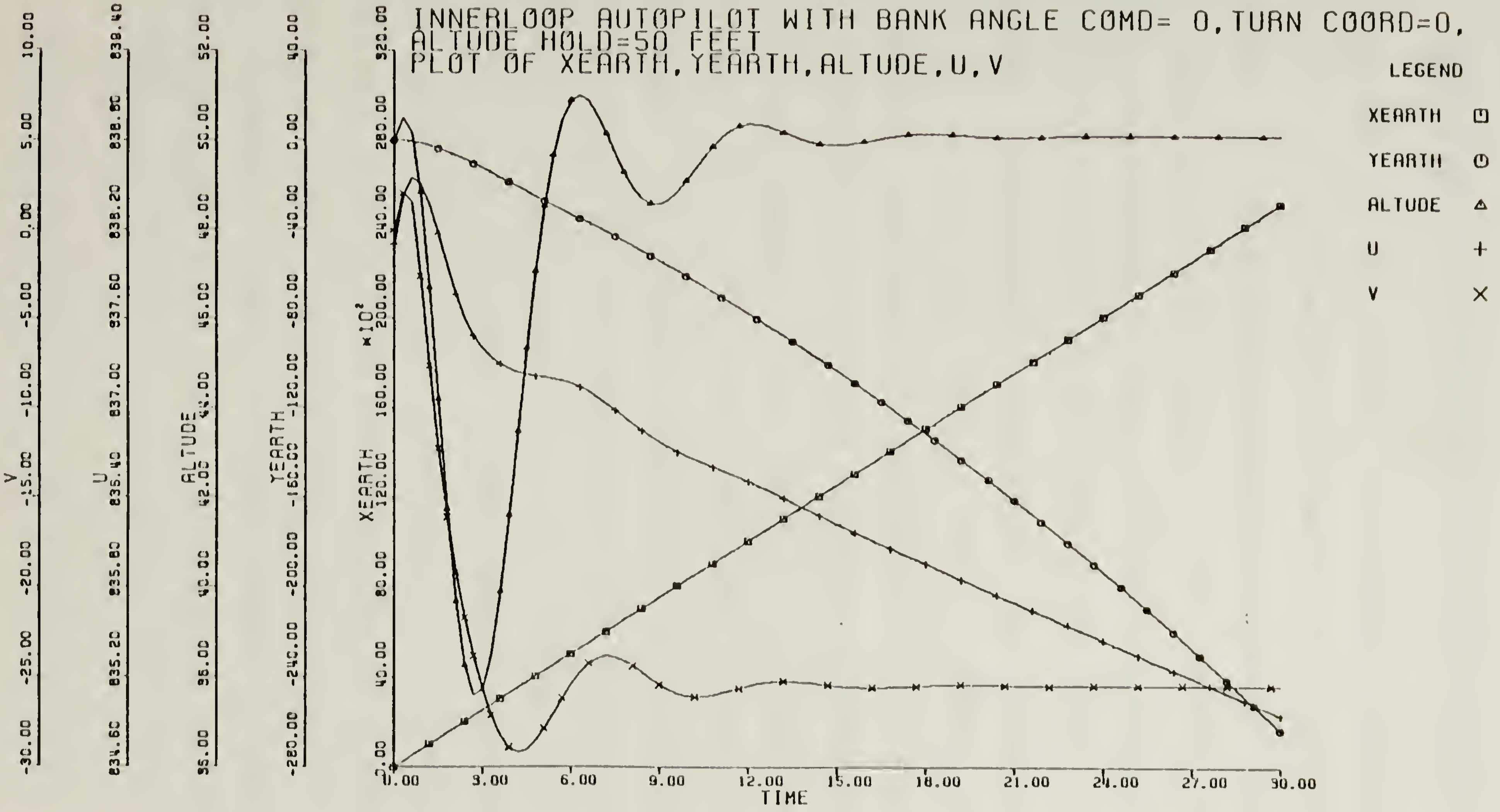


Figure 3-10 System Response to 50 ft. Altitude Hold Command

IV. DEVELOPMENT AND SIMULATION OF MISSILE GUIDANCE SYSTEM

The purpose of this study is to evaluate the effect of limited roll rate and various guidance laws on the terminal performance of a bank-to-turn cruise missile using proportional navigation in the terminal (attack) phase against a medium to large combatant ship. A baseline guidance and control scheme is designed and studied which uses a pop out maneuver, proportional navigation, and bank-to-turn maneuvering in the attack phase. The trajectory parameters and navigation constants are optimized for best performance against a moving ship utilizing blinking countermeasures. The missile is assumed to have limited roll performance due to the use of differential stabilizer for roll control vice ailerons. The terminal performance of this baseline system is evaluated for varying roll rate limits, electronic countermeasure blinking rates and burn through ranges.

A second control scheme is also designed and evaluated for the attack phase. This mode uses a sea skimming scheme in which a 50 foot altitude is maintained and proportional navigation is used in azimuth during ingress until a specified range is reached at which time proportional navigation is used in both azimuth and elevation to attack the target.

A. MISSION DESCRIPTION

1. Baseline Guidance Scheme (Pop Out Maneuver)

The mission is divided into four phases:

a) ingress

b) offset

c) popup

d) attack

The mission commences with target ship located 25,000 feet north of the missile and moving east at 21 knots. The missile initial heading is north.

The ingress phase commences with the missile flying at an altitude of 50 feet on altitude hold and utilizing proportional navigation in azimuth to home in on the target. At a given range the offset phase is initiated with a turn to the right of approximately 12 degrees followed by a commanded bank angle of zero degrees. No proportional navigation is used in this phase. At another given range a pop up maneuver is initiated which generates a low angle climb in preparation for the attack phase. During the pop up maneuver, proportional navigation is used to begin turning the missile toward the target. Finally the missile enters the attack phase at a specified range where proportional navigation is used in both vertical and azimuth planes. In this phase the bank angle is unlimited but roll rates are limited and used as one of the parameters in studying miss distances. The second parameter under study is the electronic

counter measure blinking rate frequency which is initiated at the start at the start of the attack phase and allowed to remain activated until a specified burn through range which is the third miss distance study parameter. Figure 4-1 is a geometric depiction of the missile flight path.

2. Alternate Guidance Scheme (Sea Skimmer)

The mission for this guidance scheme is divided into two phases:

a. ingress

b. attack

This mission begins with the same initial scenario as the baseline scheme, however, the pop out maneuvers (turn and pop up phases) is eliminated.

The missile flies at 50 foot altitude during the ingress phase and utilizes proportional navigation in azimuth until a range of 3000 feet at which point the missile enters the attack phase and dives in on the target using proportional navigation in both azimuth and elevation. This low altitude approach essentially resembles a sea skimming effect. Figure 4-2 shows the geometric flight profile of this scheme.

3. Electronic Counter Measures (ECM)

It is assumed that the target has the ECM capability of simultaneously shifting the aim point of the missile 75 feet aft and 10 feet vertically. The simulation is tested for ECM blinking frequencies of 0.5, 1.0, and 2.0 cycles

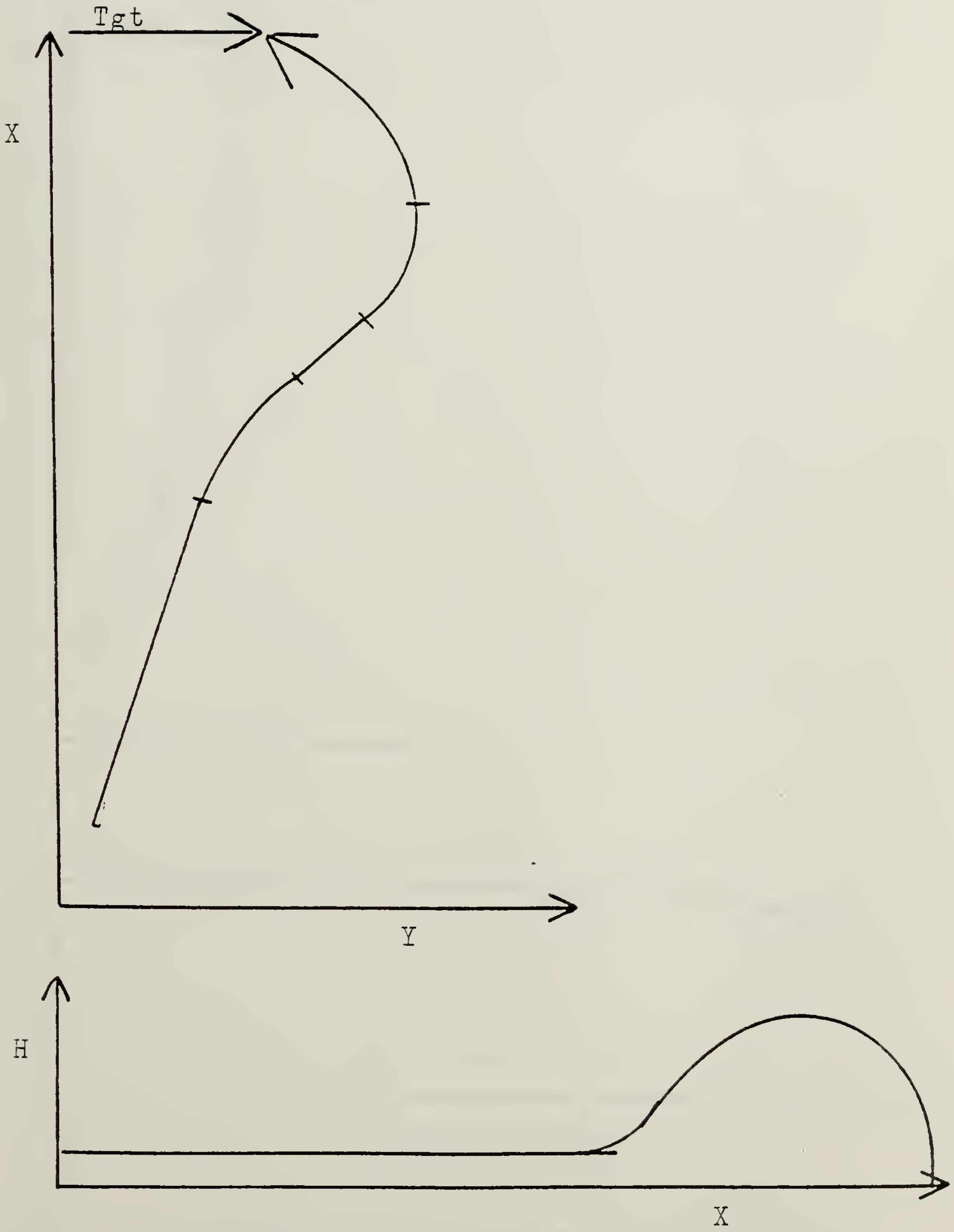


Figure 4-1 Baseline Guidance Scheme Flight Profile

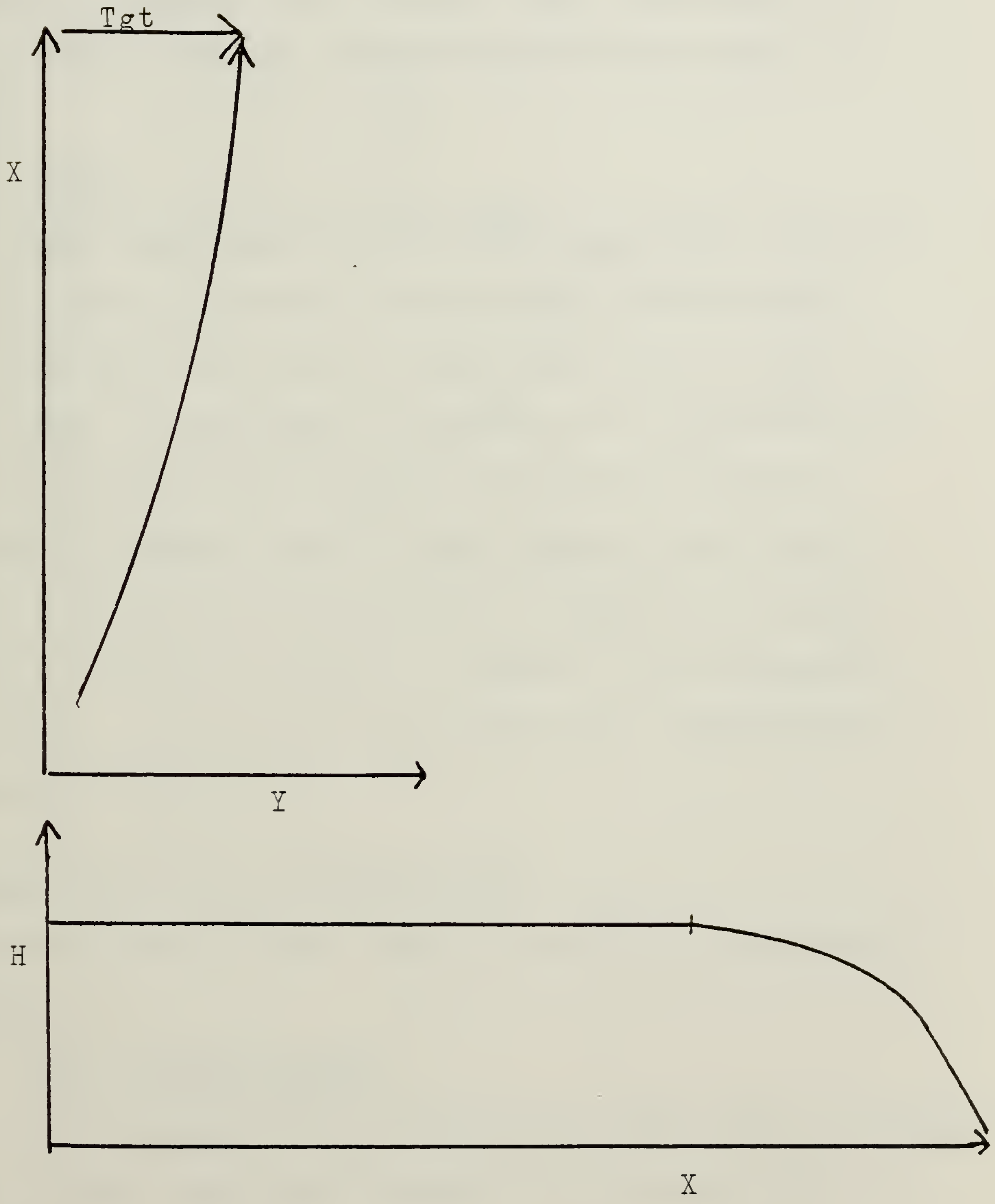


Figure 4-2 Sea Skimmer Guidance Scheme Flight Profile

per second. Blinking is commenced during the attack phase and continues until jammer burn through occurs when the target signal power can be seen over jammer power. Although 3800 feet (as calculated using Hosington, {Ref. 3}) is considered a typical burn through range the missile is tested for burn through ranges from 3800 feet down to 400 feet.

4. Glint

This study models glint with a gaussian function that gives the aim point a random shift effect with a variance of 25 feet in the Y axis and 4 feet in both the X and Z axes. Since glint is imposed as a fluctuation in target coordinates and target coordinates are used to calculate the target line of sight angles then glint is modeled as inversely proportional to range as required. For ease in simulation glint is imposed only during the attack phase. Results for runs with glint included are presented in Chapter IV.

B. SEEKER EQUATIONS AND SIMULATION

A flow diagram of the seeker simulation is presented in Figure 4-3.

1. Line of Sight Rates

It is assumed that the missile seeker has the ability to sense target range and target line of sight rates in azimuth and elevation ($\dot{\sigma}_{AZ_B}$ and $\dot{\sigma}_{EL_B}$) in the body coordinate system out to a range of 25,000 feet.

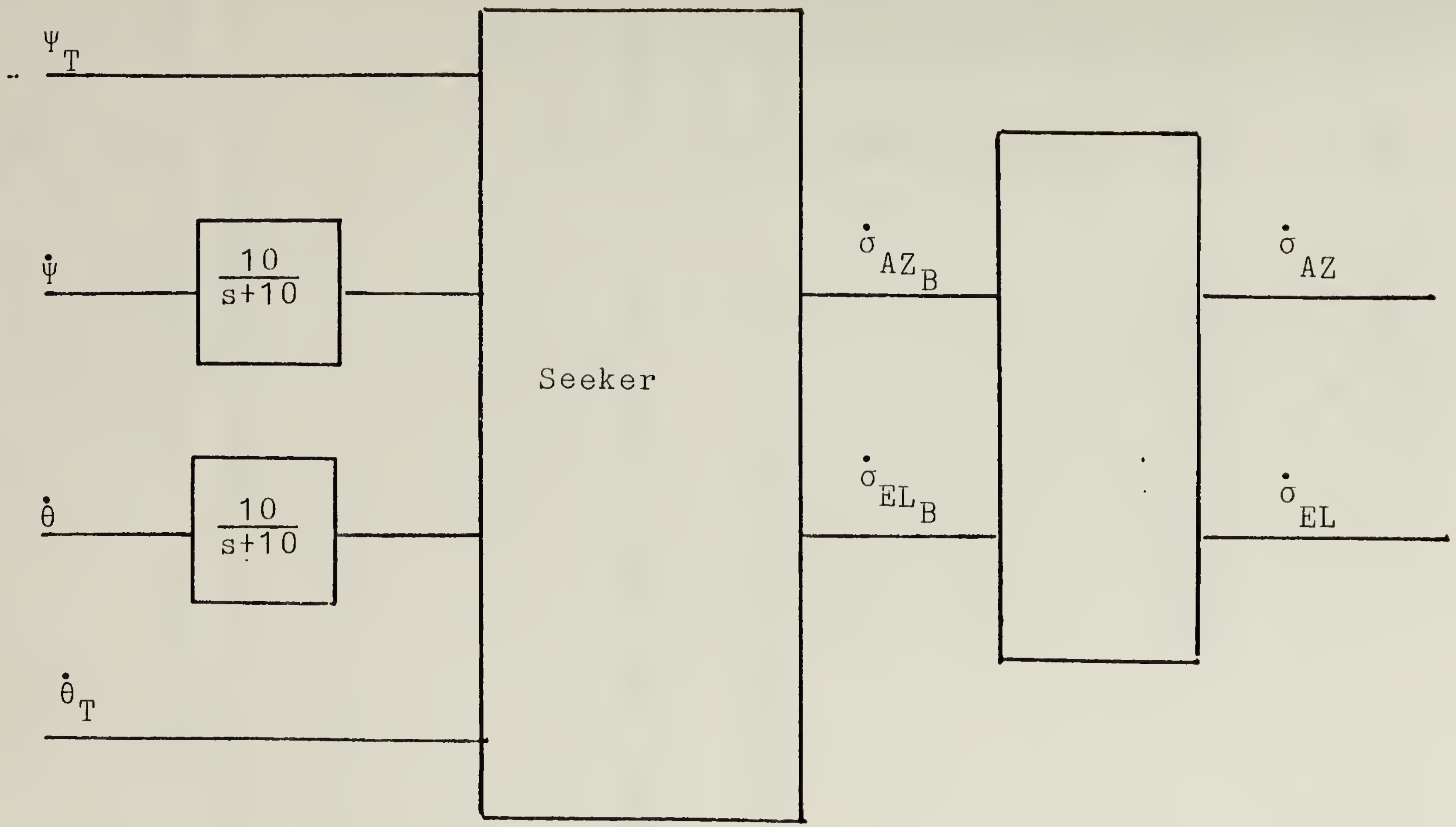


Figure 4-3 Seeker Simulation Flow Chart

These line of sight rates are generated in simulation by a two step procedure. First, the line of sight rates in earth referenced azimuth and elevation ($\dot{\sigma}_{AZ}$ and $\dot{\sigma}_{EL}$) are constructed by using the following relations:

$$\Psi_T = \tan^{-1} \frac{Y_T - Y_E}{X_T - X_E}$$

$$\theta_T = \tan^{-1} \frac{-H}{((X_T-X_E)^2+(Y_T-Y_E)^2)^{\frac{1}{2}}}$$

$$\sigma_{AZ} = \Psi_T - \Psi$$

$$\dot{\sigma}_{AZ} = \dot{\Psi}_T - \dot{\Psi}$$

$$\sigma_{EL} = \theta_T - \theta$$

$$\dot{\sigma}_{EL} = \dot{\theta}_T - \dot{\theta}$$

Figures 4-4 and 4-5 depict the geometry represented by the above equations.

Second, the body line of sight rates are calculated from the following transformation.

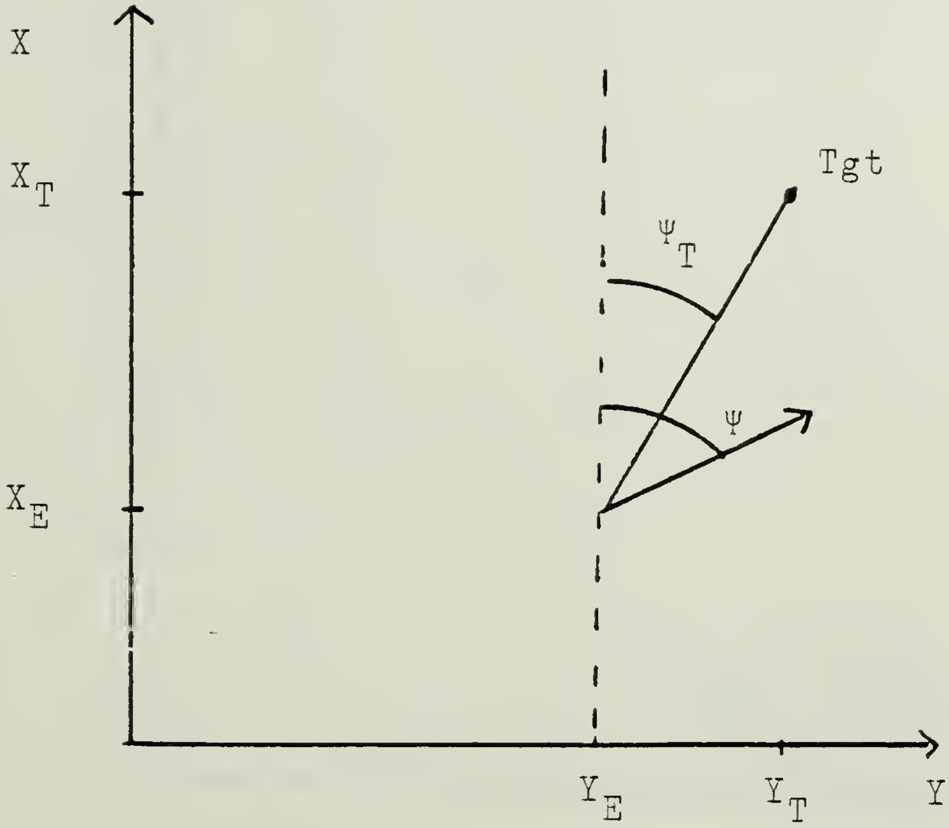
$$\dot{\sigma}_{AZ_B} = -\dot{\sigma}_{EL} \sin\phi + \dot{\sigma}_{AZ} \cos\theta \cos\phi$$

$$\dot{\sigma}_{EL_B} = \dot{\sigma}_{EL} \cos\phi + \dot{\sigma}_{AZ} \cos\theta \sin\phi$$

Once the body rates have been simulated ($\dot{\sigma}_{AZ_B}$, $\dot{\sigma}_{EL_B}$) they are transformed to earth horizontal and vertical rates through the transformation T_ϕ, defined by:

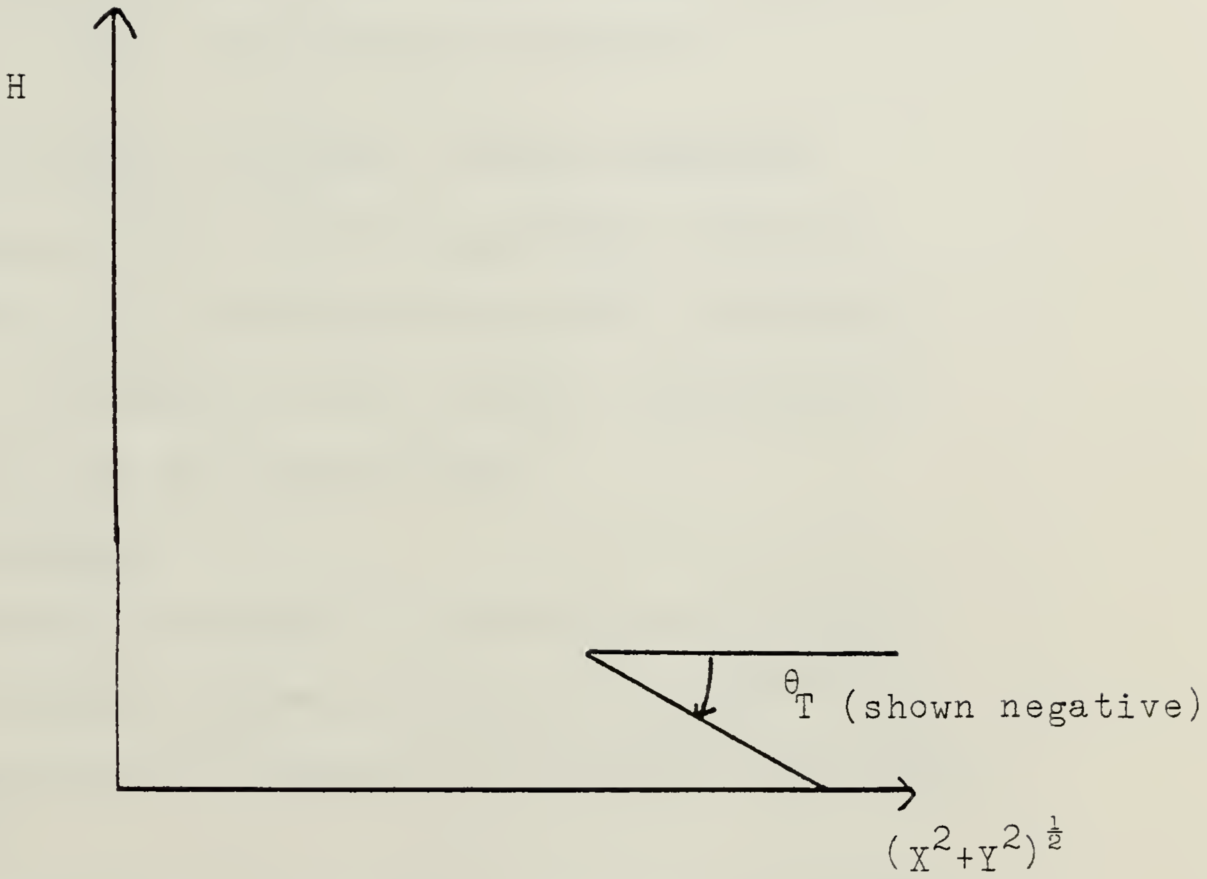
$$\dot{\sigma}_{EL} = \dot{\sigma}_{EL_B} \cos\phi - \dot{\sigma}_{AZ_B} \sin\phi$$

$$\dot{\sigma}_{AZ} = \dot{\sigma}_{EL_B} \sin\phi + \dot{\sigma}_{AZ_B} \cos\phi$$



$$\sigma_{AZ} = \Psi_T - \Psi$$

Figure 4-4 Azimuth Line of Sight Description



$$\sigma_{EL} = \theta_T - \theta$$

Figure 4-5 Elevation Line of Sight Description

This transformation includes the assumption that Θ is small throughout the mission. The earth horizontal and vertical line of sight rates ($\dot{\sigma}_{EL}$ and $\dot{\sigma}_{AZ}$) are then used in the appropriate guidance laws for proportional navigation.

2. Missile Dynamic Filters

In order to filter out missile dynamics from the seeker line of sight rates, a low pass filter, 10/(S+10), is used at the input to the seeker on $\dot{\theta}$ and $\dot{\psi}$.

C. BASELINE GUIDANCE LAW DESIGN (POPOUT MANEUVER)

A flow diagram of the baseline guidance scheme is shown in Figure 4-6. Switch positions are a function of mission phase. Each phase of the mission is described below beginning with the attack phase.

1. Attack Phase

Proportional navigation is used in azimuth and elevation to construct guidance commands to the missile autopilot commencing at a range of 9100 feet in the manner described below.

a. Proportional Navigation Constants and Guidance Commands

The earth horizontal and vertical line of sight rates ($\dot{\sigma}_{AZ}$ and $\dot{\sigma}_{EL}$) which are generated from the body rates $\dot{\sigma}_{AZ_B}$ and $\dot{\sigma}_{EL_B}$ by the transformation T_ϕ are multiplied by a navigation constant and V_T/g to generate commanded lateral accelerations in the earth vertical and horizontal planes.

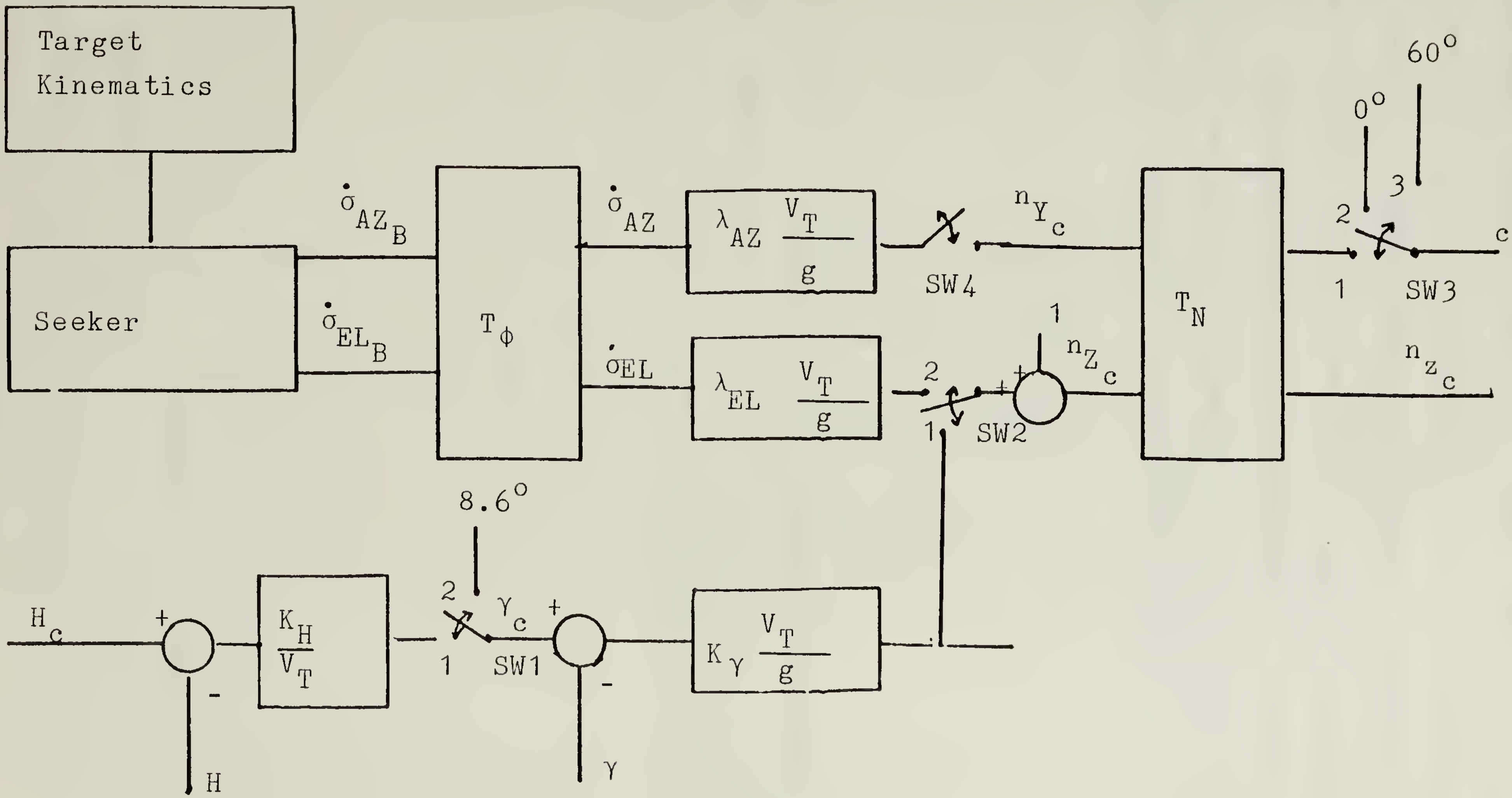


Figure 4-6 Baseline Guidance Law Flow Diagram

A navigation constant of 4.0 in each plane was found to yield best results. Values from 3.0 to 4.5 were evaluated with results of that evaluation shown in Chapter V. A one g bias is applied to the vertical commanded lateral acceleration to compensate for acceleration due to gravity. Thus two lateral acceleration commands (n_{Y_c} and n_{Z_c}) are computed in the earth horizontal and vertical planes.

$$n_{Y_c} = \lambda_{AZ} \frac{V_T}{g} \dot{\sigma}_{AZ} \qquad (13)$$

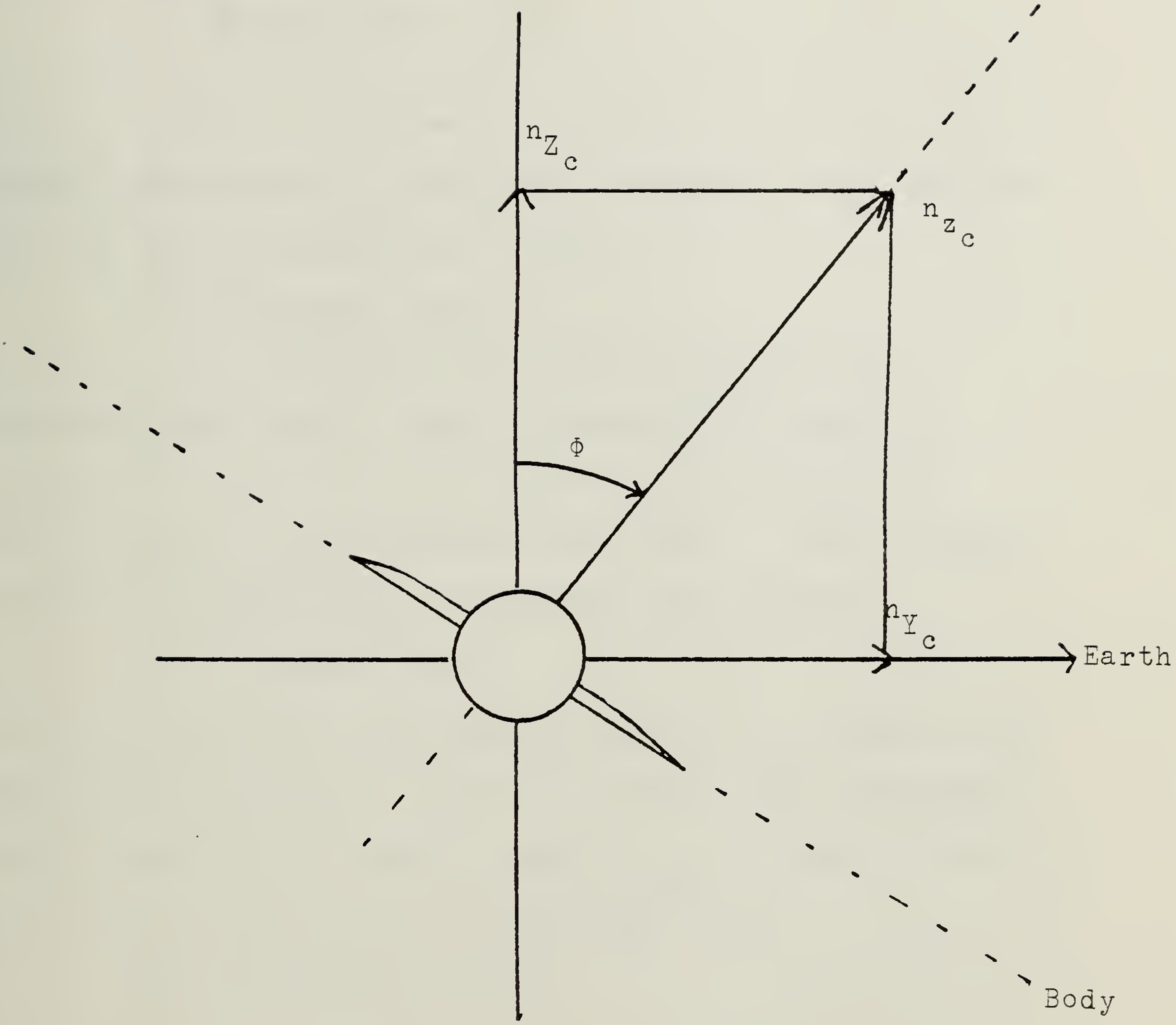
$$n_{Z_c} = \lambda_{EL} \frac{V_T}{g} \dot{\sigma}_{EL} + 1 \qquad (14)$$

These commanded lateral accelerations are subjected to a further transformation (T_N) in order to generate commanded bank angle and normal load factor which are required by the missile autopilot.

$$\phi_C = \tan^{-1} \frac{n_{Y_c}}{n_{Z_c}}$$

$$n_{z_c} = n_{Z_c} \cos\phi + n_{Y_c} \sin\phi$$

Figure 4-7 depicts the geometric relationship described by the above two equations. Commanded bank angle (ϕ_C) and normal load factor (n_{z_c}) are used as inputs to the appropriate autopilot outer command loops to provide closed loop bank angle and load factor responses.



- - - - - Body Coordinate System
——— Earth Coordinate System

Figure 4-7 Load Factor and Bank Angle Description

b. Limits on Guidance Commands

In the attack phase, the following limits are applied to commanded variables:

$$-2 \leq n_{z_c} \leq 4$$

$$|\dot{\phi}_c| \leq \dot{\phi}_{max}$$

Missile performance is evaluated for maximum roll rates of 50, 100 and 200 degrees per second.

c. Bank Angle Anomoly

In the attack mode there is no limit on commanded bank angle. Thus a computational scheme is required to insure that the missile always rolls the shortest way to a new commanded bank angle. This is accomplished by continuously calculating the quantity:

$$\Delta(t) = |\phi_c(t) - \phi(t)|$$

If $\Delta(t)$ is less than 180 degrees then $\phi_c(t)$ is sent to the bank angle autopilot. If $\Delta(t)$ is greater than 180 degrees then a modified bank angle command (ϕ_{c_M}) is sent to the auto pilot in accordance with the following logic:

$$\phi_{c_M} = \phi_c + 360^\circ \text{ for } \phi_c < 0$$

$$\phi_{c_M} = \phi_c - 360^\circ \text{ for } \phi_c > 0$$

d. Switch Positions

The switches shown in figure 4-6 are in the following positions for the attack phase:

SW1 Either position

SW2 Position 2

SW3 Position 1

SW4 Closed

e. Attack Phase Summary

In the attack phase proportional navigation is used in both azimuth and elevation to generate bank angle and normal load factor commands to the missile autopilot. The phase is commenced at a range of 9100 feet with missile offset in heading from the target at an altitude of approximately 250 feet. Roll rate is limited to ϕ_{max}. Bank angle is not limited. Normal load factor is limited from -2 to 4 g's.

2. Ingress Phase

The ingress phase commences with the beginning of the problem simulation when the missile is 25,000 feet from the target and initially heading north. The missile's Mach number is 0.75 and the ship's velocity is 21 knots to the east.

a. Altitude Hold Methodology and Guidance Commands

The missile is required to maintain altitude of 50 feet above sea level during this phase. It accomplishes this by comparing present altitude with 50 feet and multiplying the error by $\frac{K_H}{V_T}$ to establish a flight path angle command. K_H is assigned a value of 0.3. This calculated flight path angle command is compared with the present flight path angle

and the difference or error is multiplied by K_H and $\frac{V_T}{g}$ to give an elevation line of sight rate, $\dot{\sigma}_{EL}$. A value of 0.3 is assigned for K_H. Thus n_{Z_c} is computed as follows:

$$n_{Z_c} = K_H \frac{V_T}{g} (\gamma_c - \gamma) + 1$$

The lateral acceleration command n_{Y_c} is computed exactly as described in the attack phase with bank angle and roll rates limited.

The second transformation for the ingress phase (T_N) remains the same form as the attack phase.

$$\phi_c = \tan^{-1} \frac{n_{y_c}}{n_{z_c}}$$

$$n_{z_c} = n_{Z_c} \cos\phi + n_{Y_c} \sin\phi$$

b. Limits on Guidance Commands

In the ingress phase the following limits are applied to commanded variables:

$$-2 \leq n_{z_c} \leq 4$$

$$|\phi_c| \leq |\phi_{max}|$$

$$|\dot{\phi}_c| \leq |\dot{\phi}_{max}|$$

The maximum bank angle allowed is 60 degrees and roll rate is limited to 50,100 or 200 degrees per second.

c. Switch Positions

The switch positions as shown in Figure 4-6 are as follows during the ingress phase:

SW1, SW2, SW3	Position 1
SW4	Closed

3. Offset Phase

The missile initiates the offset phase at 17,800 feet. The offset phase is subdivided into two sub-phases -- turn and level.

a. Turn and Level Sub-Phases

The missile maintains an altitude of 50 feet throughout the offset phase in the same manner as described during the ingress phase. Thus

$$n_{Z_c} = K_\gamma \frac{V_T}{g} (\gamma_c - \gamma) + 1$$

The missile performs the coordinated turn by using a commanded bank angle and computing a normal load factor as follows:

$$\phi_C = 60^\circ$$

$$n_{z_c} = \frac{n_{Z_c}}{\cos\ \phi}$$

At a range of 15800 feet from the target a turn of approximately 12 degrees is accomplished. The missile then performs a straight and level maneuver by commanding zero bank angle along with the same normal load factor as follows:

$$\phi_C = 0^\circ$$

$$n_{z_c} = \frac{n_{Z_c}}{\cos\ \phi}$$

b. Limits on Guidance Commands

For the offset phase normal load factor is limited as follows:

$$-2 \le n_{z_c} \le 4$$

Commanded bank angle is fixed at 60 degrees during the turn sub-phase and 0 degrees during the level sub-phase.

c. Switch Positions

The switch position, as shown in Figure 4-6, are as follows during the offset phase:

1) Turn sub-phase

SW1, SW2	Position 1
SW3	Position 3
SW4	Open

2) Level sub-phase

SW1, SW2	Position 1
SW3	Position 2
SW4	Open

4. Pop Up Phase

The missile enters the pop up phase when the range becomes 10,200 feet. The purpose of this phase is to pop up the missile to an altitude of approximately 250 feet so that a dive into the target will give acceptable deck penetration.

a. Vertical Flight Path Angle Methodology and Guidance Commands

The missile achieves the pop up effect by commanding a vertical flight path angle of 8.6 degrees.

This commanded climb angle is compared with the actual γ and the error is multiplied by K_γ and $\frac{V_T}{g}$ to give an elevation line of sight rate. A value of 1.0 is assigned for $K\gamma$ in this simulation. Thus n_{Z_c} is computed as follows:

$$n_{Z_c} = K_\gamma \frac{V_T}{g} (\gamma_{climb} - \gamma) + 1$$

The lateral acceleration commanded n_{y_c} is computed exactly as described in the ingress phase.

The second transformation T_N is as follows:

$$\phi_c = \tan^{-1} \frac{n_{y_c}}{n_{Z_c}}$$

$$n_{z_c} = n_{Z_c} \cos\phi + n_{Y_c} \sin\phi$$

The missile is free to start rolling into the target using proportional navigation during the pop up phase and thus aids in the attack phase which follows the pop up phase.

b. Limits on Guidance Commands

In the pop up phase the following limits are applied to commanded variables:

$$-2 \leq n_{z_c} \leq 4$$

$$|\phi_c| \leq |\phi_{max}|$$

$$|\phi_c| \leq |\phi_{max}|$$

The maximum bank angle is limited to 60 degrees and the maximum roll rate is limited to 50, 100 or 200 degrees per second.

c. Switch Positions

The switch positions as shown in Figure 4-6 are as follows during the pop up phase:

SW1	Position 2
SW2, SW3	Position 1
SW4	Closed

5. Guidance Summary (Baseline)

The following matrix indicates the horizontal and vertical controls during each phase of missile flight.

PHASE	AZIMUTH CONTROL	ELEVATION CONTROL
Ingress	PN*	Altitude Hold
Offset	ϕ Command	Altitude Hold
Popup	PN	Flight Path Angle Hold
Attack	PN	PN

*Proportional Navigation

D. ALTERNATE GUIDANCE LAW DESIGN SEA-SKIMMER

The sea skimmer scheme differs only from the baseline guidance scheme in that the offset and popup phases are eliminated. In essence this scheme is composed of an ingress phase and an attack phase.

1. Ingress Phase

The ingress phase commences with problem initialization which locates the missile 25,000 feet from the target with

identical initial conditions as the baseline guidance scheme. The vertical load factor is computed as

$$n_{Z_c} = K_H \frac{V_T}{g} (\gamma_c - \gamma) + 1$$

The lateral acceleration command is computed as

$$n_{Y_c} = \lambda_{AZ} \frac{V_T}{g} \dot{\sigma}_{AZ}$$

The second transformation (T_N) is as follows:

$$\phi_C = \tan^{-1} \frac{n_{Y_c}}{n_{Z_c}}$$

and $$n_{z_c} = n_{Z_c} \cos\phi + n_{Y_c} \sin\phi$$

Limits on guidance commands and switch positions for the ingress phase are identical to the ingress phase for the baseline scheme.

2. Attack Phase

The attack phase commences at 3000 feet range and uses proportional navigation in both elevation and azimuth. The missile dives into the target from 50 foot altitude.

The bank angle command and normal load factor are computed exactly as in the baseline scheme attack phase and are:

$$\phi_C = \tan^{-1} \frac{n_{Y_c}}{n_{Z_c}}$$

$$n_{z_c} = n_{Z_c} \cos\phi + n_{Y_c} \sin\phi$$

Limits on guidance commands and switch positions are also identical to the attack phase in the baseline guidance scheme.

3. Guidance Summary (Sea Skimmer)

The following matrix shows the horizontal and vertical controls during each phase of the sea skimmer guidance scheme.

PHASE	AZIMUTH CONTROL	VERTICAL CONTROL
Ingress	PN	Altitude Hold
Attack	PN	PN

V. PROBLEM SIMULATION, RESULTS, CONCLUSIONS AND RECOMMENDATIONS

This chapter describes the computer simulation special language used and presents the results of test runs in which roll rate, ECM blinking rate and burn through range are all varied in both the baseline guidance scheme and the sea skimming guidance scheme. From these results optimum parameters are chosen to yield minimum miss distance for each guidance scheme. Miss distance ranges are also presented for the baseline scheme with Glint imposed.

A. CSMP SIMULATION

The Continuous System Modeling Program III (CSMP III), an IBM developed system, is the modeling technique chosen for this study. CSMP, as discussed in Speclchart and Green {Ref. 4}, is compatable with the Fortran IV language, has six selectable integration methods (fourth order Runge-Kutta is used for this simulation), and has multiple special function codes that can solve a large variety of control engineering problems.

The special functions used for this simulation are:

a. FUNGEN - This function extracts the value of a function of one variable from a stored table in memory. It is used for aerodynamic coefficients.

b. TWOVAR - This function extracts the value of a function of two variables from a stored table in memory. It is used for aerodynamic coefficients.

c. INSW - Y = INSW (X1, X2, X3) assigns Y = X2 for $X_1 < 0$, $Y = X_3$ for $X_1 \geq 0$. It is used to accomplish ECM blinking action.

d. GAUSS - This function is a random number generator with normal distribution. It is used to realize glint.

e. REALPL - This function simulates a first order lag $1/(\tau S++1)$ filter. It is used in autopilot and seeker equations as low pass filters.

f. DEBUG - This is a computer program aid that evaluates all output parameters and variables at requested times.

In addition to the special functions, trigonometric, integral, derivative and square root functions are used to perform necessary steps with one invocation. CSMP also has the ability to perform calculations in either a sort section, where the order of computation is not considered, or a nosort section, where ordered sequential fortran statements are required. The program is structured as shows below:

MISSILE SIMULATION PROGRAM

```
INITIAL

        CONSTANTS
        AERODYNAMIC COEFFICIENT TABLES

DYNAMIC
    NOSORT

        MISSION PHASE LOGIC
        GUIDANCE EQUATIONS
        ECM (BLINKING) EQUATIONS

    SORT

        6 DOF MISSILE DYNAMIC EQUATIONS
```

INNER LOOP AUTOPILOTS
SEEKER EQUATIONS

TERMINAL

OUTPUT GRAPHS

The CSMP initially sets up the two and three variable coefficients in tabular form in memory. The run commences with the missile in steady state flight with steady state variables established. These steady state variables are used to enter the tables in memory and extract coefficients which are used to calculate aerodynamic derivatives, forces, moments, and other relations. From the steady state flight condition small perturbations are made and new table entries produced. This process is repeated for all phases of flight.

B. RESULTS

Both the baseline guidance scheme and the sea skim guidance scheme were tested under the same conditions and quantitative results obtained. All scenarios started from the following initial conditions:

1. Target position - 25,000 feet north of the missile.
2. Target speed - east at 21 knots.
3. Missile speed - north at 0.75 Mach number
4. Missile altitude - 50 feet above sea level.

The simulation was run for 31 seconds. Miss distance data was obtained for varying roll rate limits, ECM blinking frequencies, and burn through ranges. The following matrix of parameters was tested:

Burn through range (feet)

2000
1500
1200
800
400

Roll rate limit (degrees per second)

200
100
50

ECM blinking frequency (Hertz)

2
1
0.5

The resulting miss distances are shown in Tables 5-1 and 5-2 for all runs. Figure 5-1 through figure 5-6 are the graphical results of simulation runs. Each run is presented in 6 consecutive figures a through f and depict the following.

a. Commanded roll rate (PCMD) and roll rate (P) vs time.

b. Commanded bank angle (PHICMD) and bank angle (PHI) vs time.

c. Range, X Range, Y Range and Z Range vs time.

d. Left and right stabilizers (LSTAB and RSTAB) vs time.

e. Rudder position vs time.

f. Map of YMISLE and HMISLE vs XMISLE.

The following matrix indicates the test conditions used to generate each figure:

TABLE 5-1

Baseline Guidance and Control Scheme

Miss Distance (feet)

ECM Blinking Rate	Roll Rate Limit	Burnthrough Ranges				
		400	800	1200	1500	2000
.5 cps	50	19.9	15.7	16	16	6.28
	100	17	11.3	6.95	6.95	18.16
	200	27	30	29	29	26.1
1 cps	50	24	23	11.3	9.8	10.7
	100	12.6	13.7	12.5	11	6.9
	200	5.4	3	4.9	2.9	6.57
2 cps	50	25	20	8.9	6.6	4.34
	100	23.7	15.7	2.2	1.69	6.8
	200	13.3	7.9	1.5	4.2	6.81
0 cps	50	2.5				
	100	4.4				
	200	4.5				

TABLE 5-2

Sea-Skimmer Guidance and Control Scheme

Miss Distance (feet)

ECM Blinking Rates	Roll Rate Limit	Burnthrough Ranges				
		400	800	1200	1500	2000
.5	50	43	37.7	37.7	37.7	2.8
	100	72	61	61	61	1.56
	200	44.64	28.7	37.7	28.7	1.77
1	50	54	54	38.62	28.8	1.48
	100	52	52	20	20.6	3.9
	200	65	63	26	26	3.09
2	50	34.6	31.20	37.7	37.7	2.87
	100	32.9	27.9	61	61	1.56
	200	43.5	37.35	28.8	28.8	1.77
0	50	3.9				
	100	2.7				
	200	2.6				

BASE GUIDANCE SCHEME

5-1 (a-f) NO ECM, 100°/sec roll rate

5-2 (a-f) ECM (1Hz), 100°/sec roll rate

5-3 (a-f) ECM (1Hz), 50°/sec roll rate

5-4 (a-f) ECM (1Hz), 200°/sec roll rate

SEA SKIMMER SCHEME

5-5 (a-f) NO ECM, 100°/sec roll rate

5-6 (a-f) ECM (1Hz), 100°/sec roll rate

1. Analysis of Baseline Scheme Results

a. Varying Burn Through Range

Miss distances generally decrease as the burn through range increases. For runs beyond 1500 feet burn through ranges, the miss distances are close enough to be considered as hits since most of the miss distance is in the Y component of range which has the largest offset (75 feet) applied during ECM.

b. Varying ECM Blinking Frequency

The miss distance decreases as blinking rate increases for the same burn through range. Miss distances for burn through ranges beyond 1200 feet are particularly good for all three roll rates.

c. Varying Roll Rate Limit

Varying roll rate limit results in the largest variation in miss distance. For 200 degree per second roll rate limit and 0.5 Hertz ECM blinking frequency the

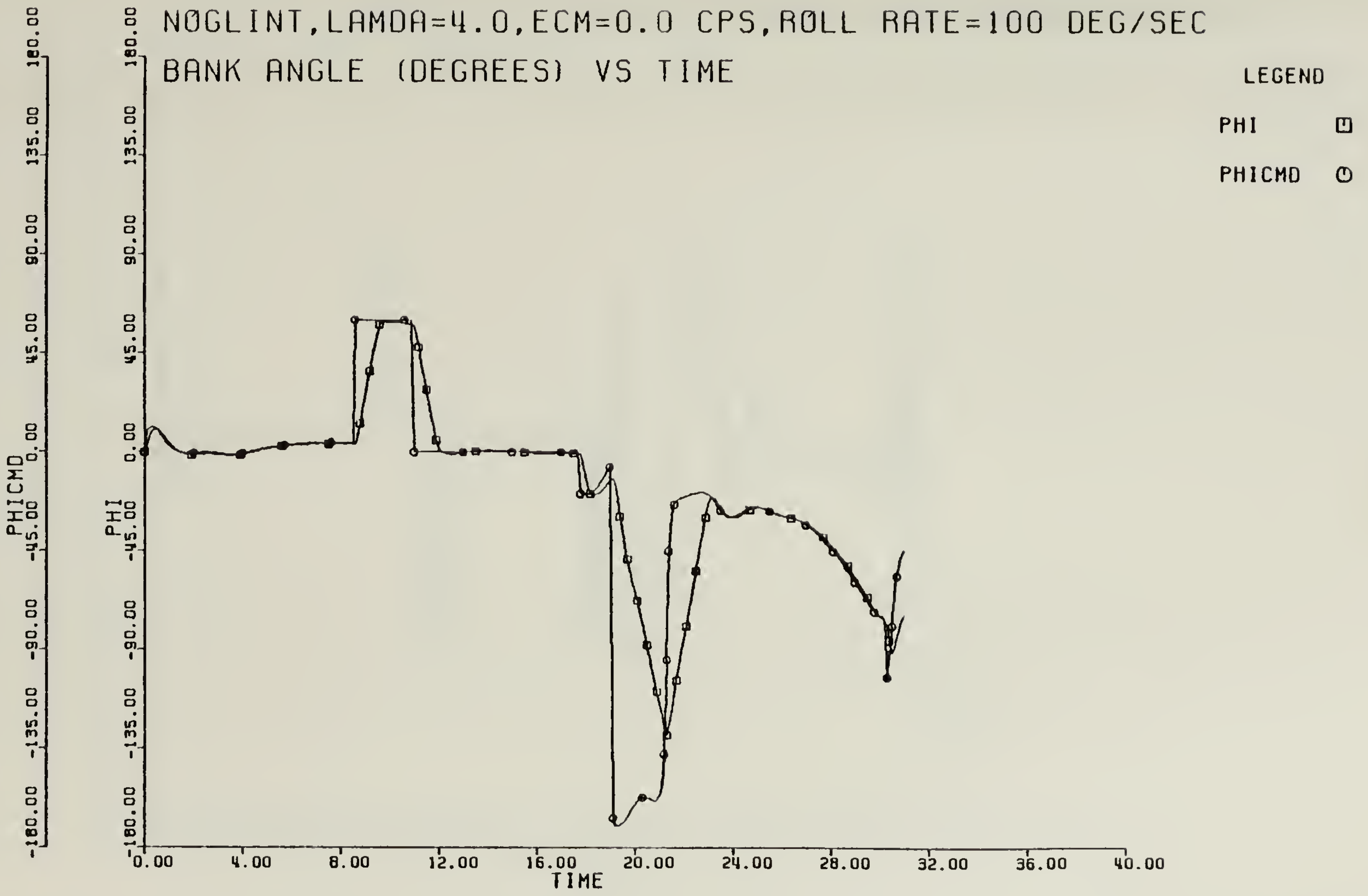


Figure 5-1a Baseline Response for No ECM, Roll Rate Limit 100 deg/sec

(PHICMD, PHI vs TIME)

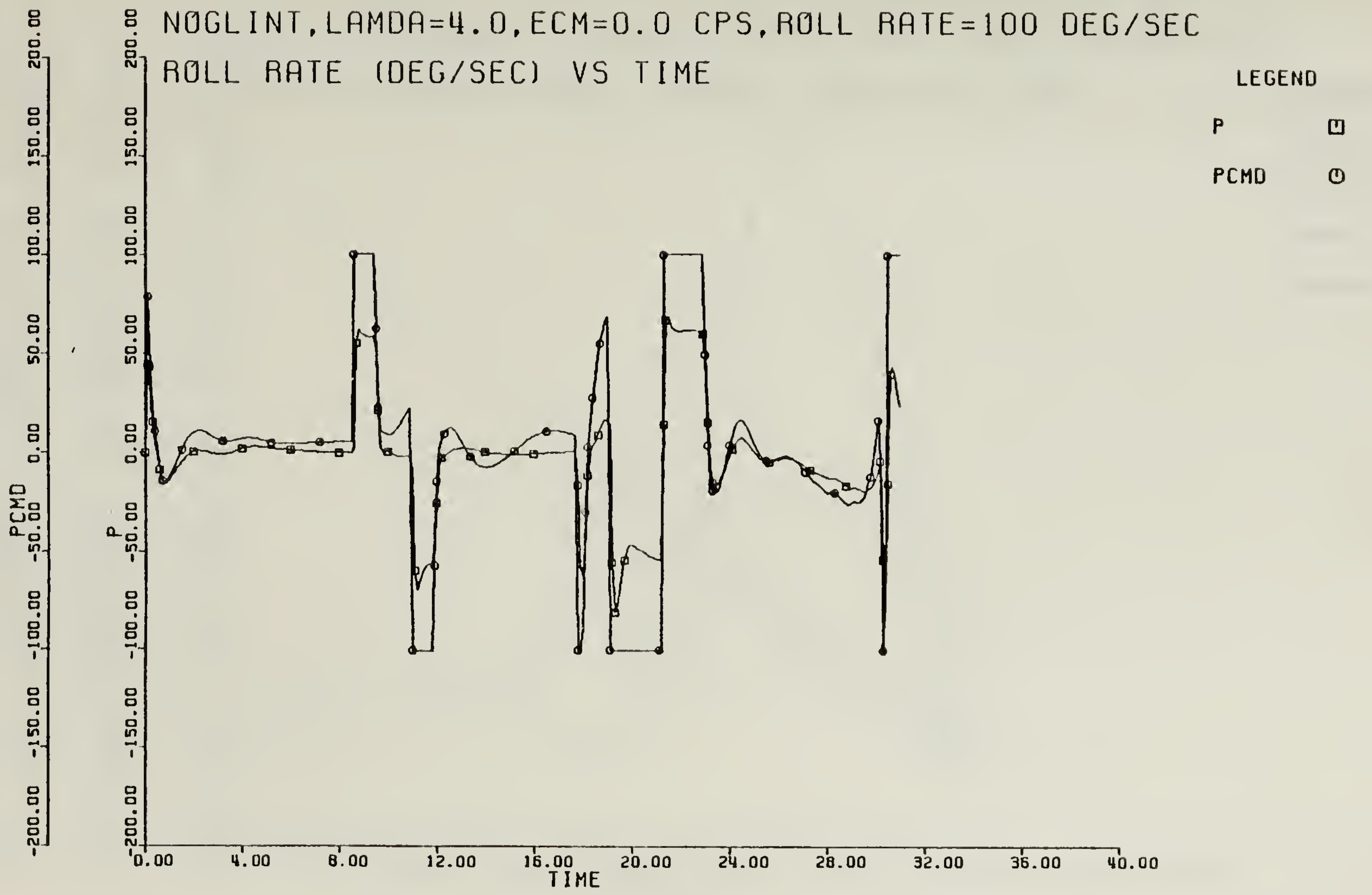


Figure 5-1b Baseline Response for No ECM, Roll Rate Limit 100 deg/sec

(PCMD, P vs TIME)

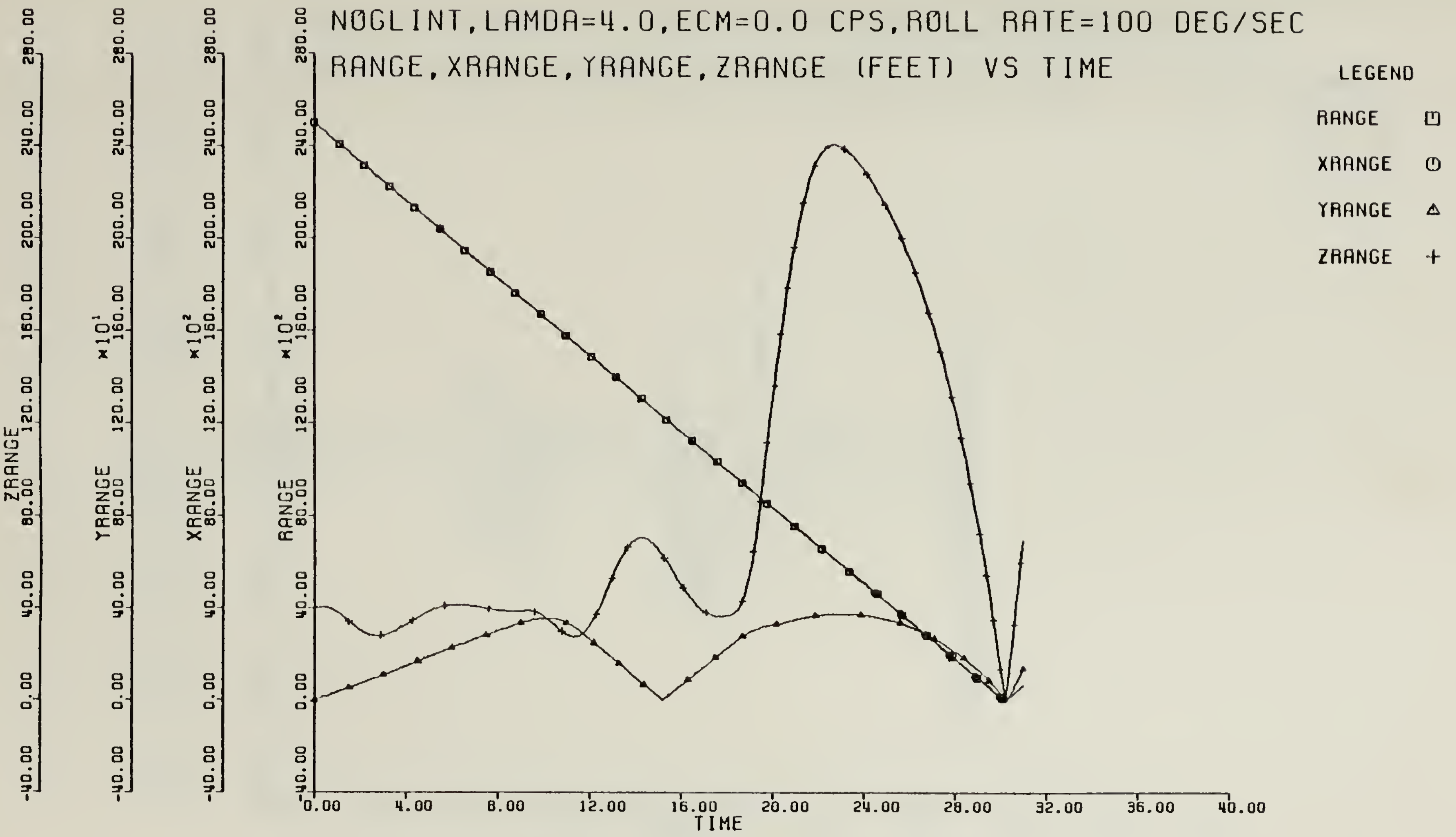


Figure 5-1c Baseline Response for No ECM, Roll Rate Limit 100 deg/sec

(RANGE, XRANGE, YRANGE, ZRANGE vs TIME)

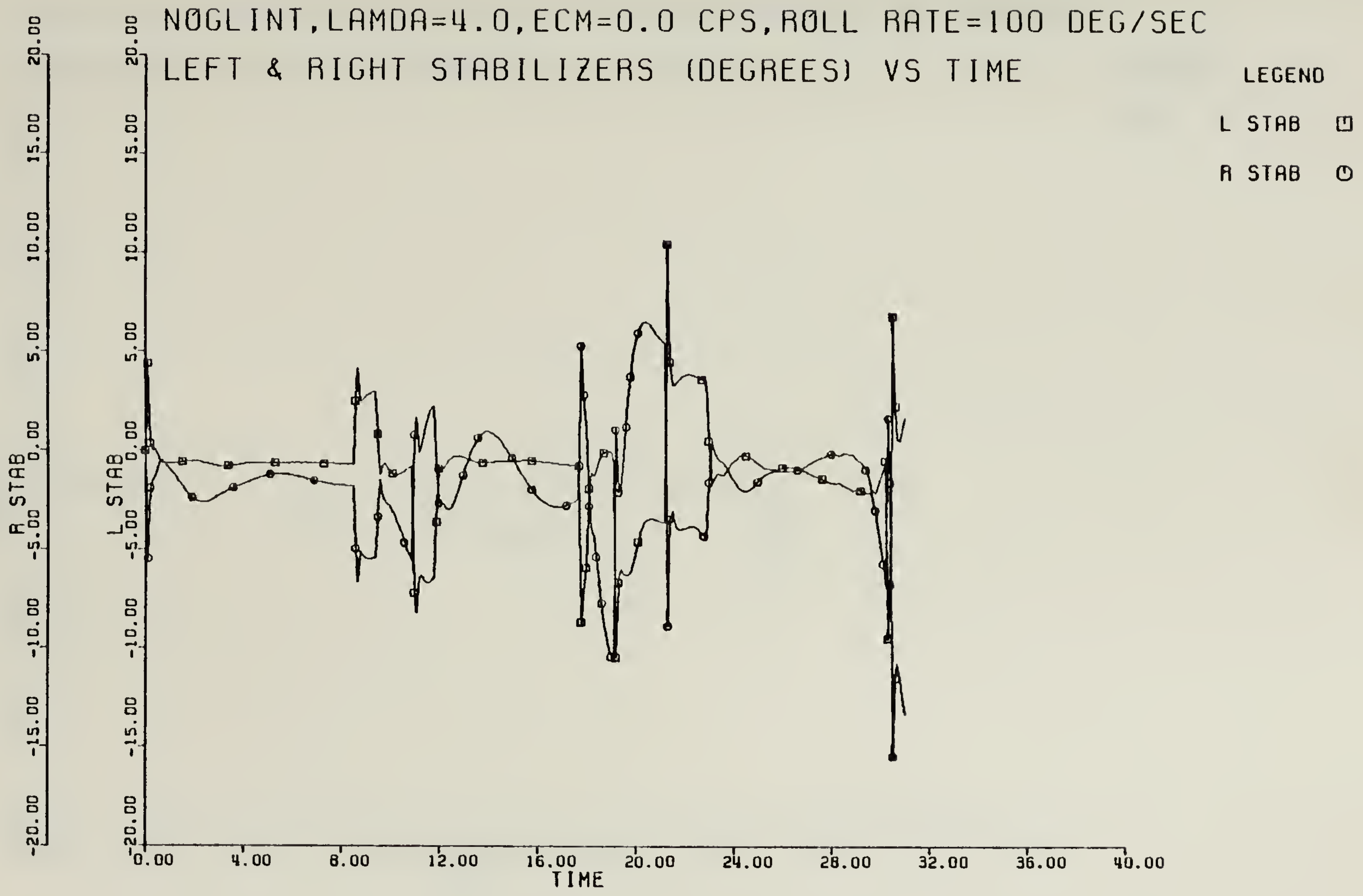


Figure 5-1d Baseline Response for No ECM, Roll Rate Limit 100 deg/sec

(L STAB, R STAB vs TIME)

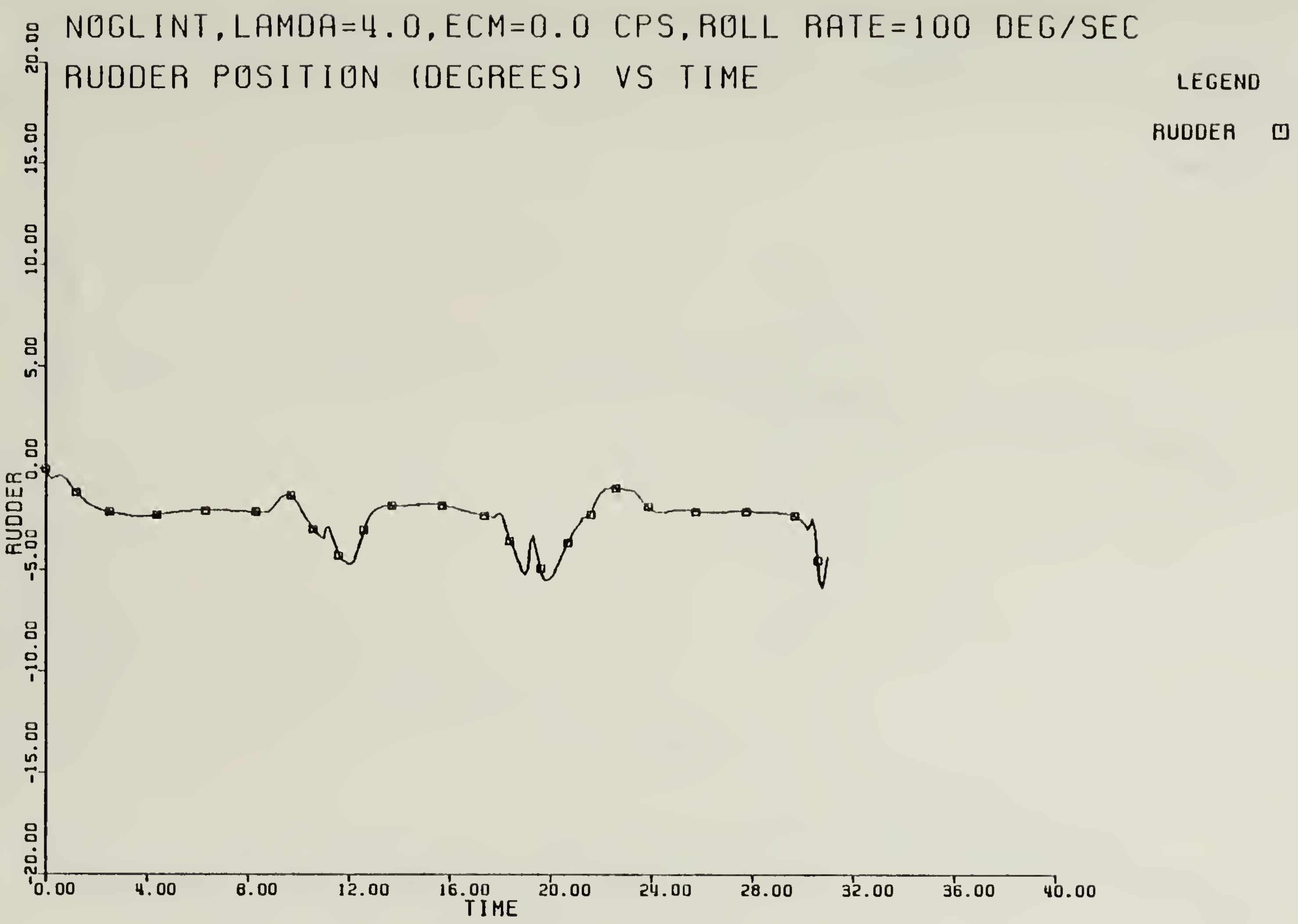


Figure 5-1e Baseline Response for No ECM, Roll Rate Limit 100 deg/sec

(RUDDER vs TIME)

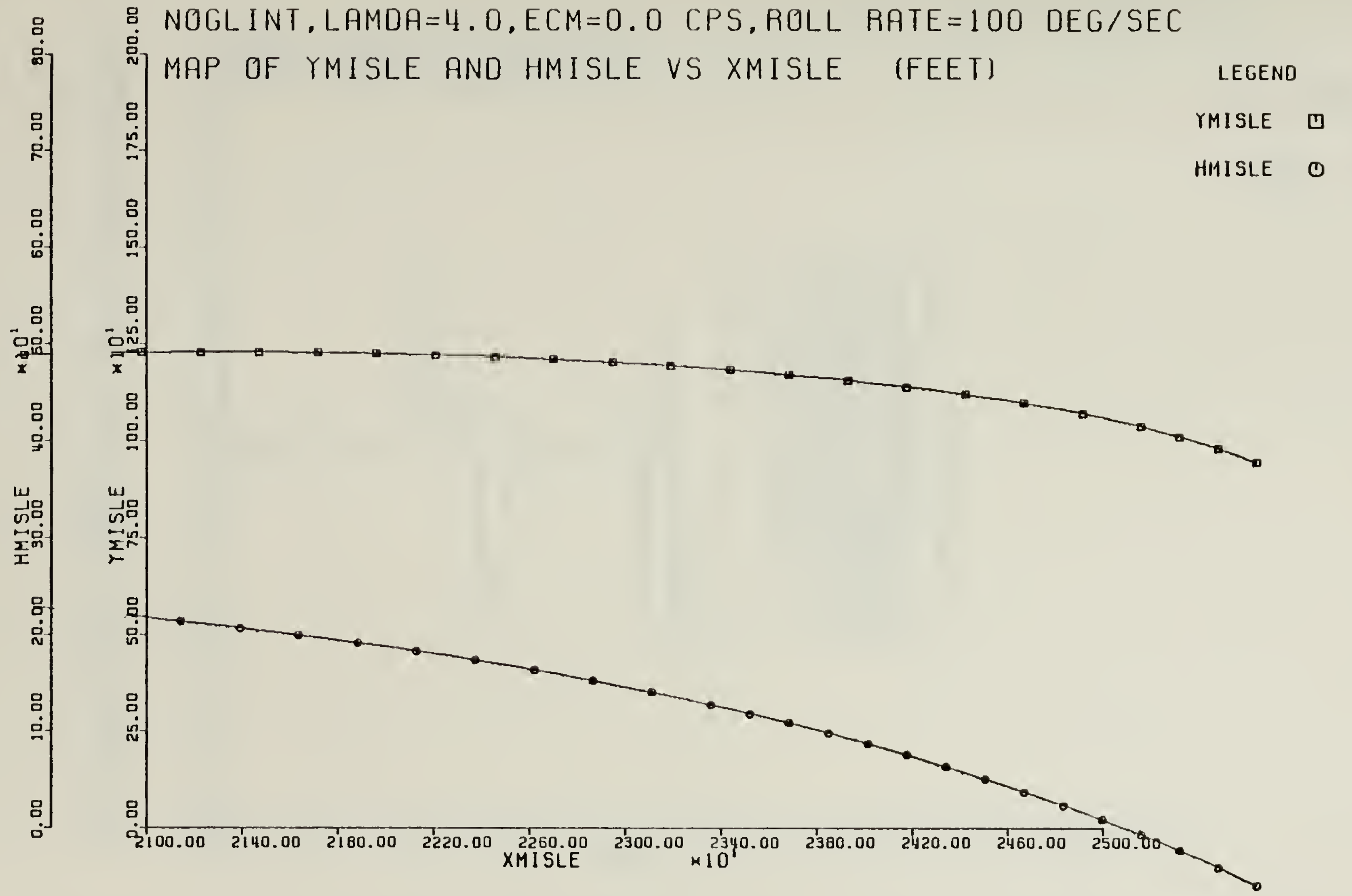


Figure 5-1f Baseline Response for No ECM, Roll Rate Limit 100 deg/sec

YMISLE, HMISLE vs XMISLE)

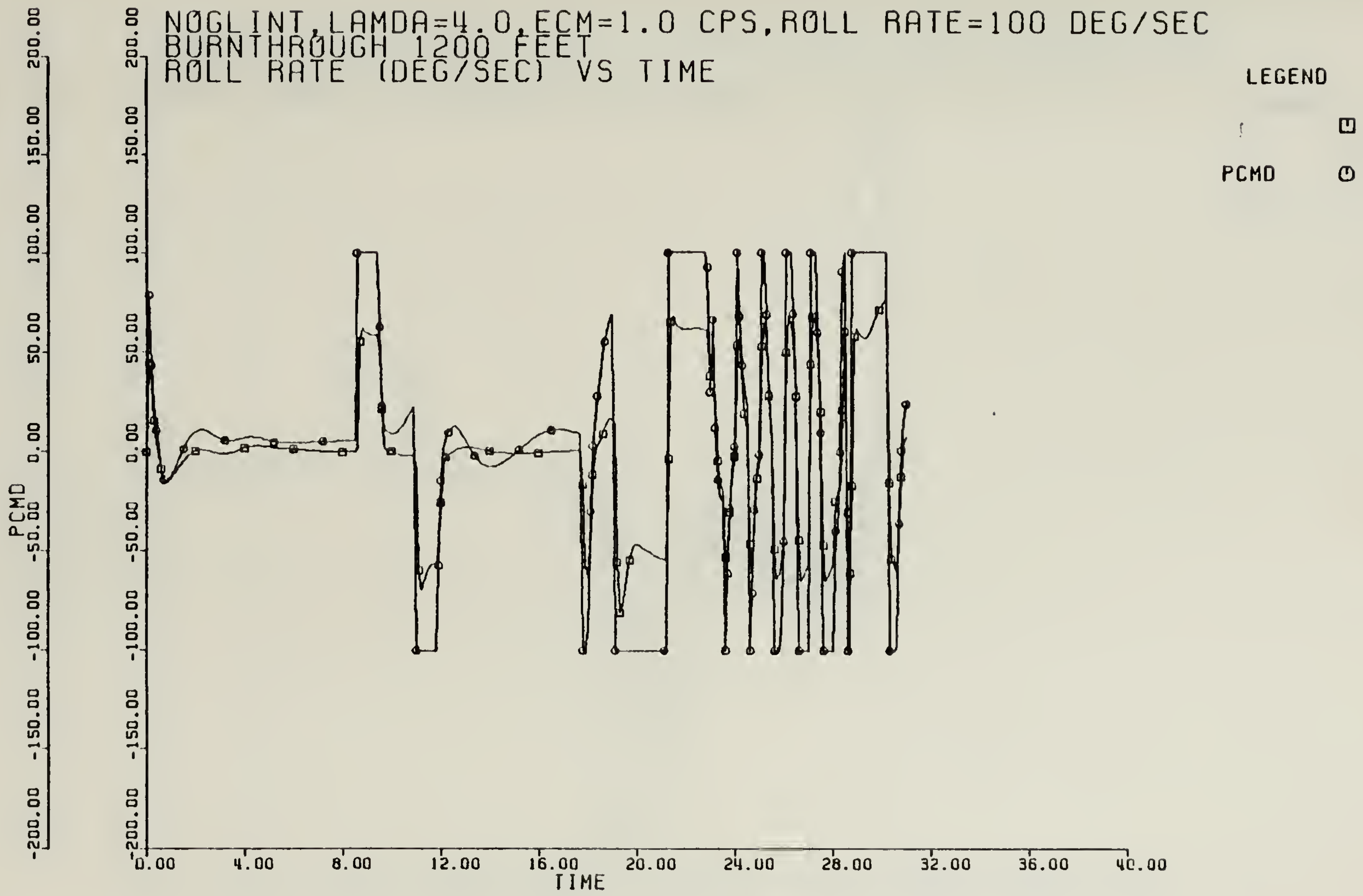


Figure 5-2a Baseline Response for ECM 1 CPS, Roll Rate Limit 100 deg/sec

(PCMD,P vs TIME)

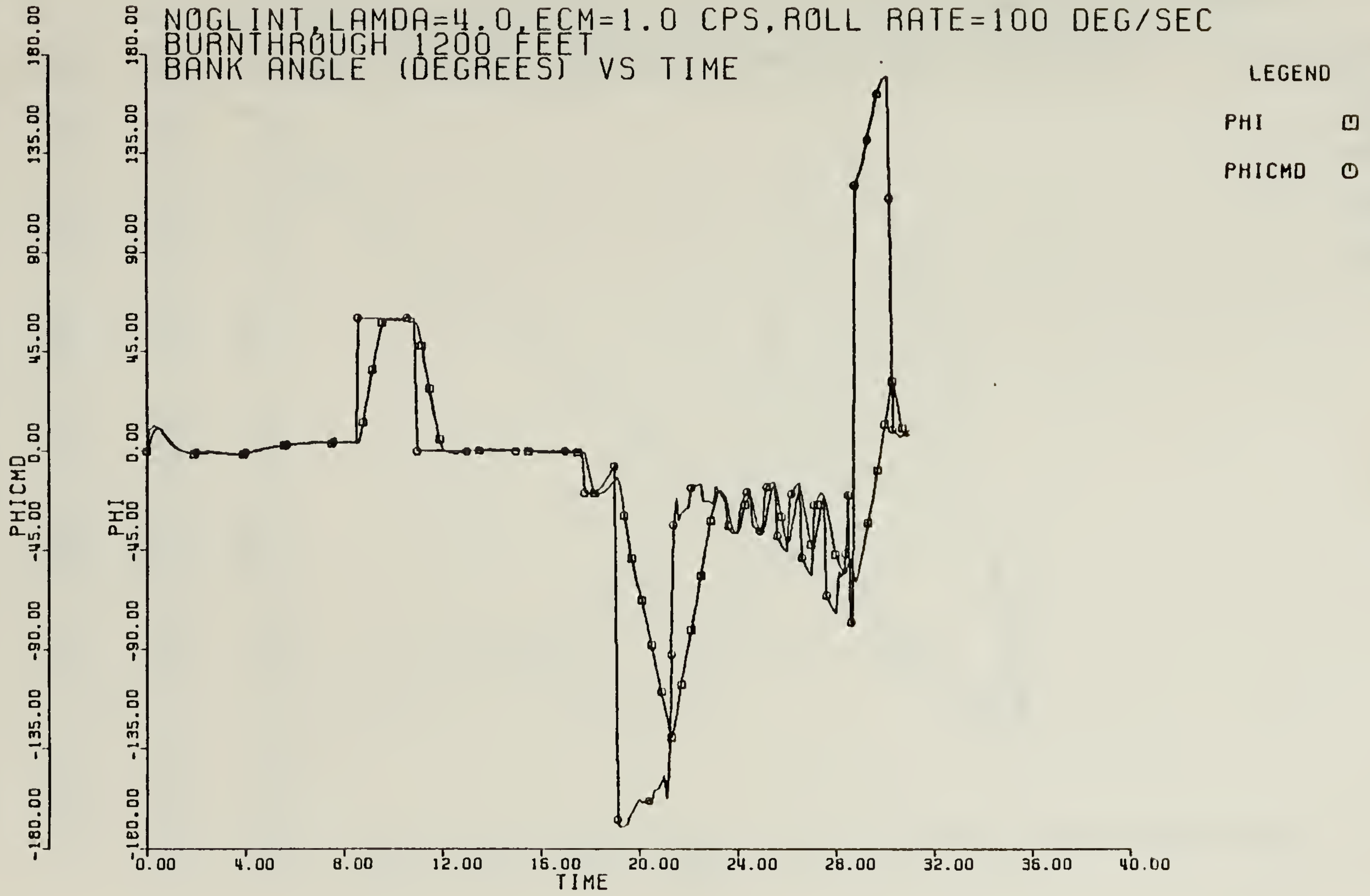


Figure 5-2b Baseline Response for ECM 1 CPS, Roll Rate Limit 100 deg/sec

(PHICMD, PHI vs TIME)

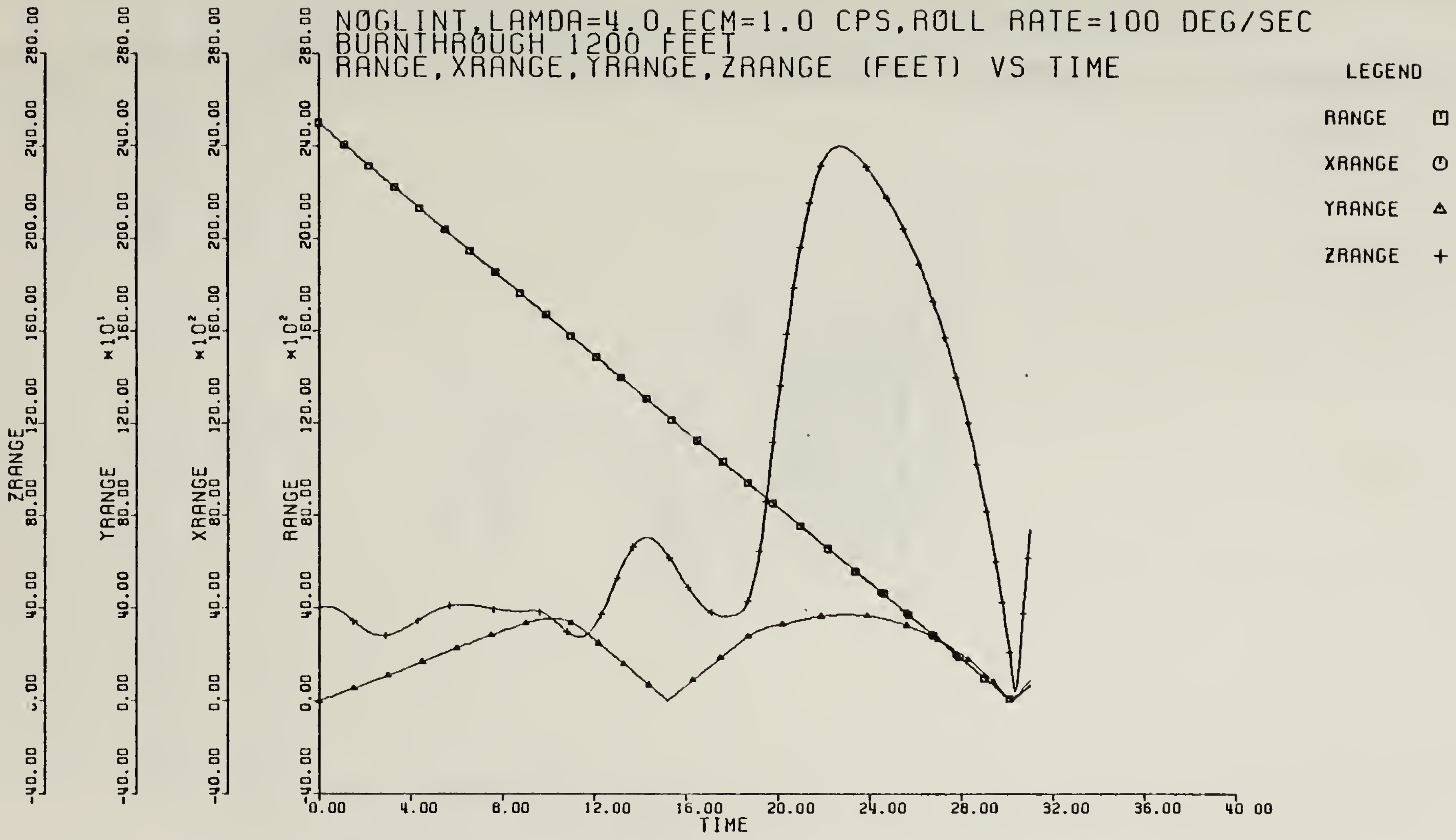


Figure 5-2c Baseline Response for ECM 1 CPS, Roll Rate Limit 100 deg/sec

(RANGE, XRANGE, YRANGE, ZRANGE vs TIME)

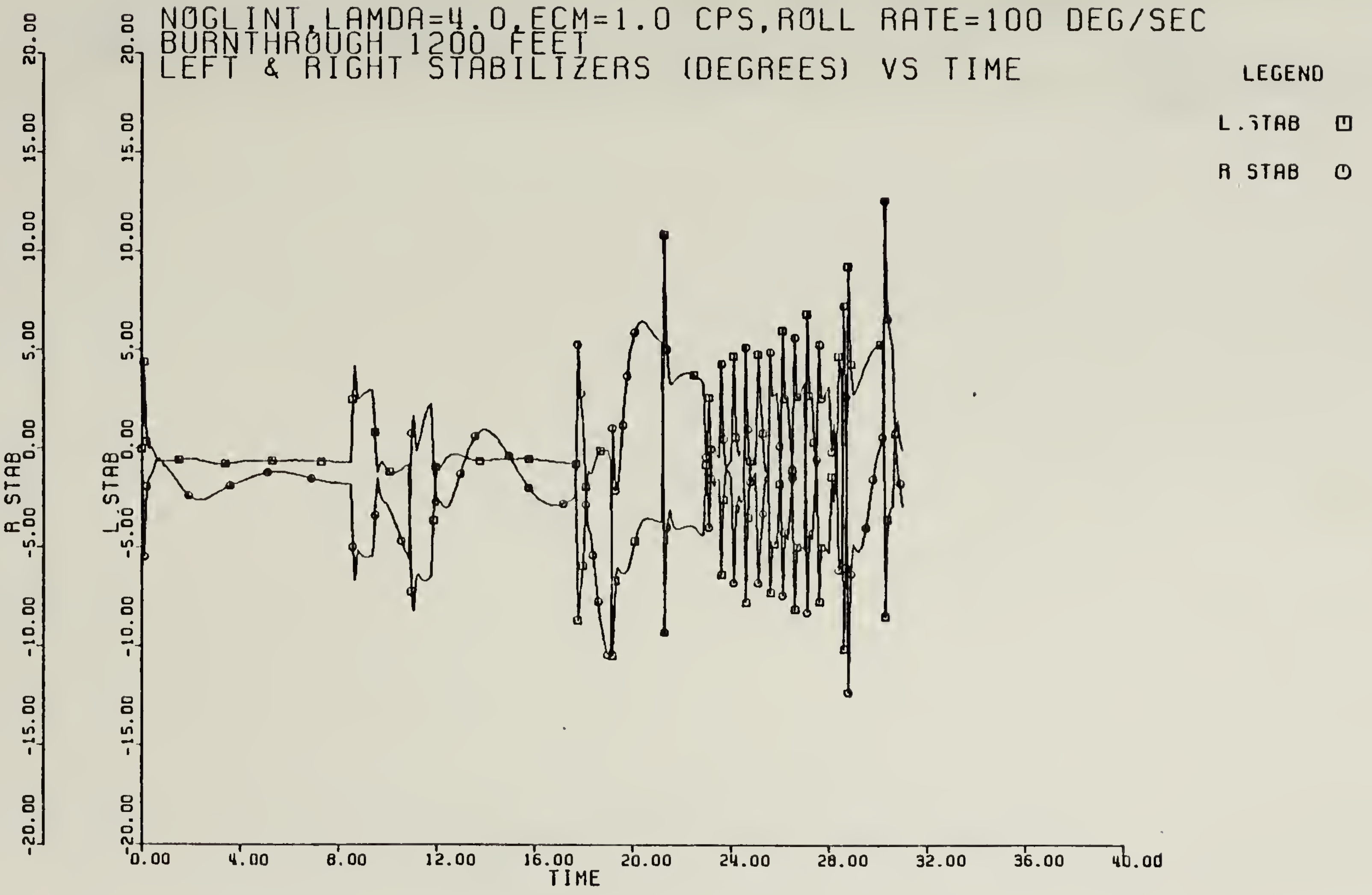


Figure 5-2d Baseline Response for ECM 1 CPS, Roll Rate Limit 100 deg/sec

(L STAB, R STAB vs TIME)

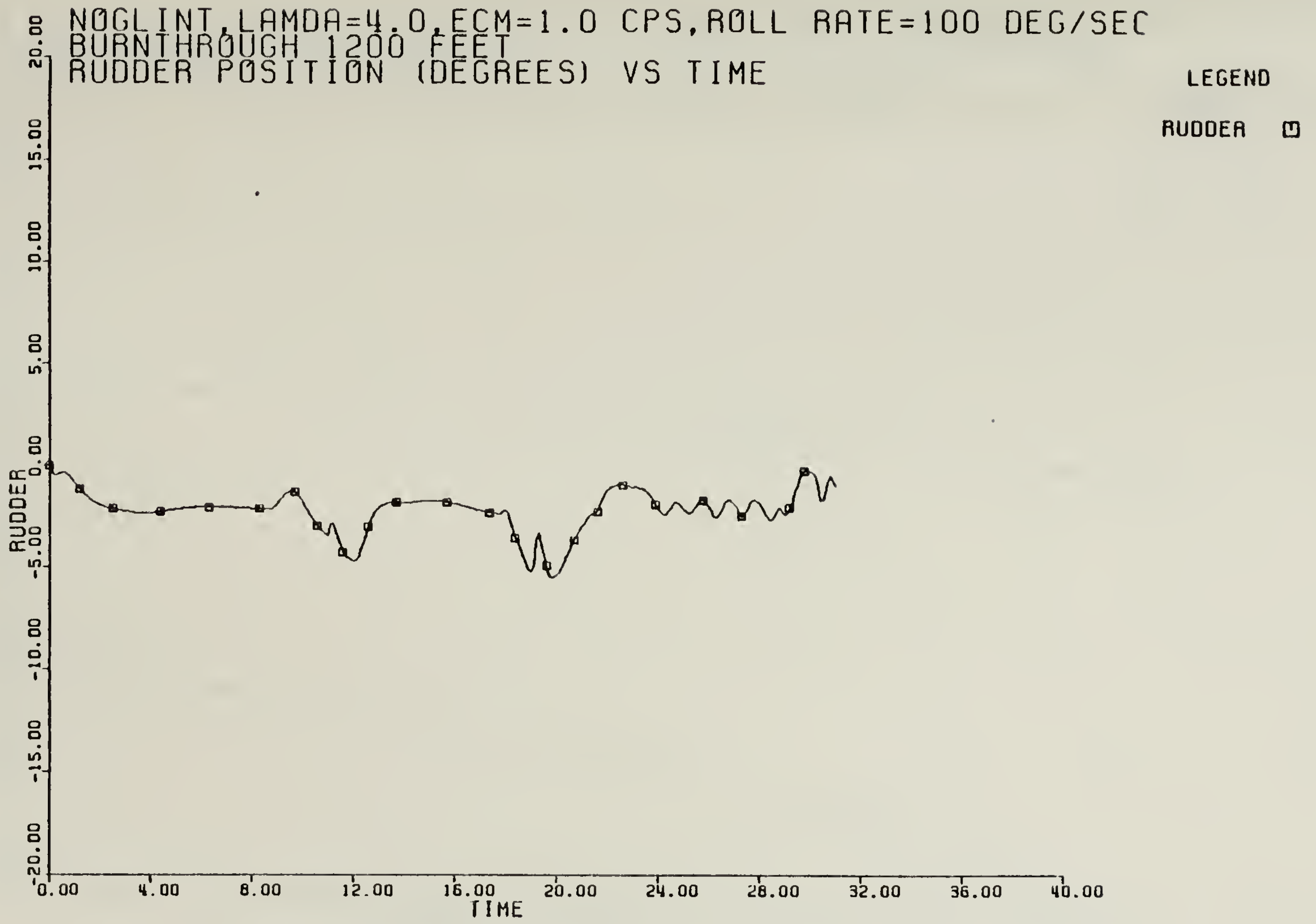


Figure 5-2e Baseline Response for ECM 1 CPS, Roll Rate Limit 100 deg/sec

(RUDDER vs TIME)

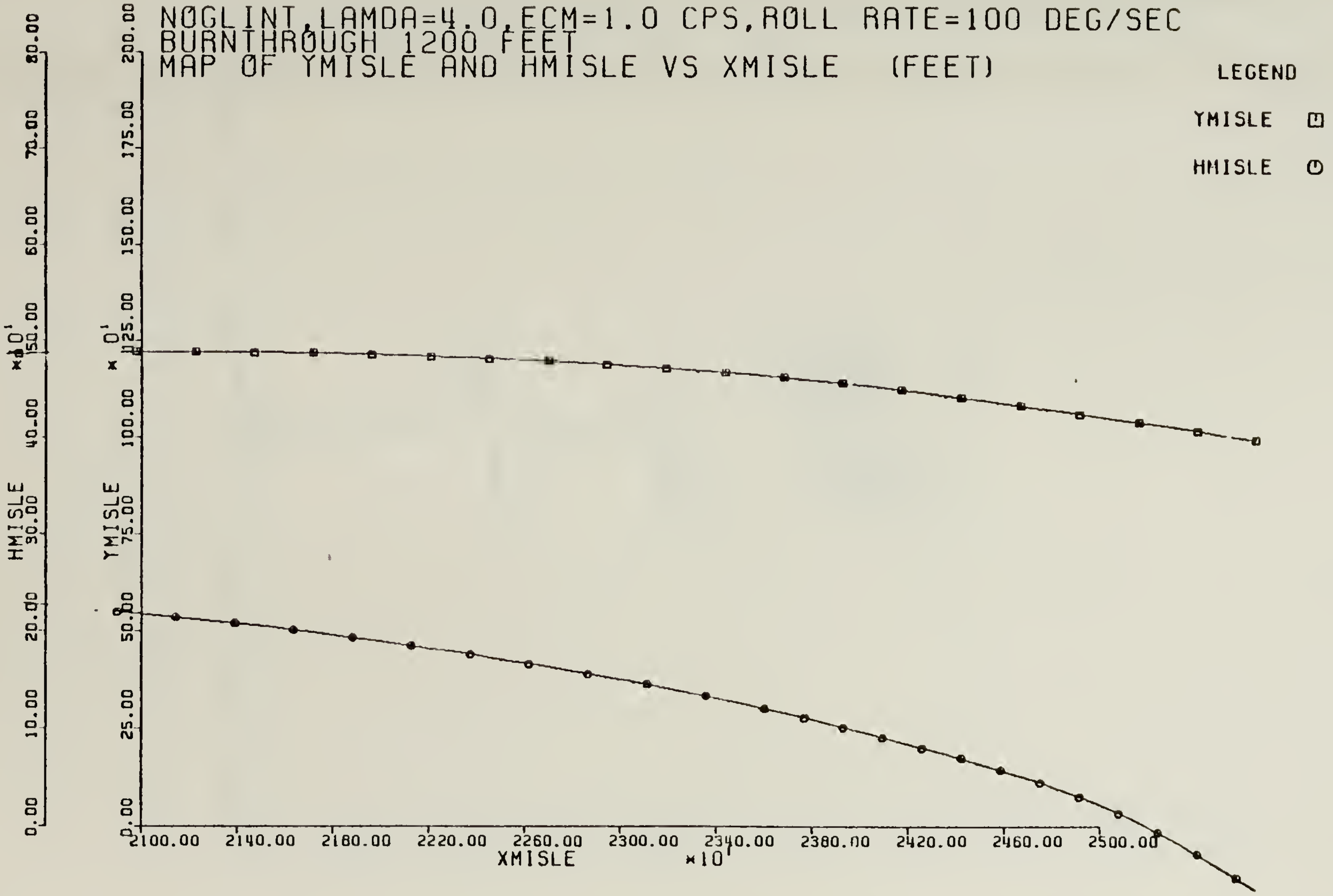


Figure 5-2f Baseline Response for ECM 1 CPS, Roll Rate Limit 100 deg/sec

(YMISLE, HMISLE vs XMISLE)

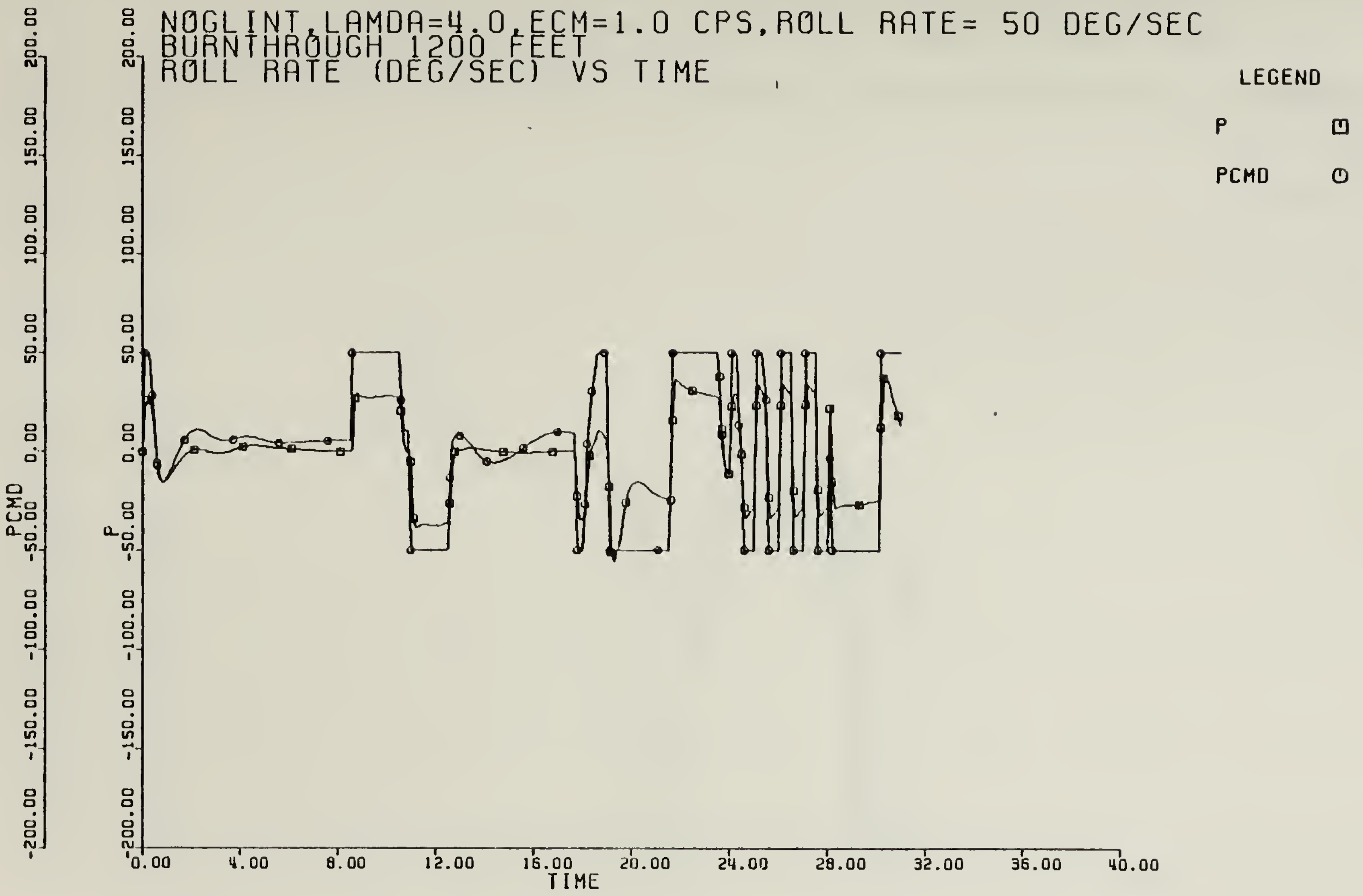


Figure 5-3a Baseline Response for ECM 1 CPS, Roll Rate Limit 50 deg/sec

(PCMD, P vs TIME)

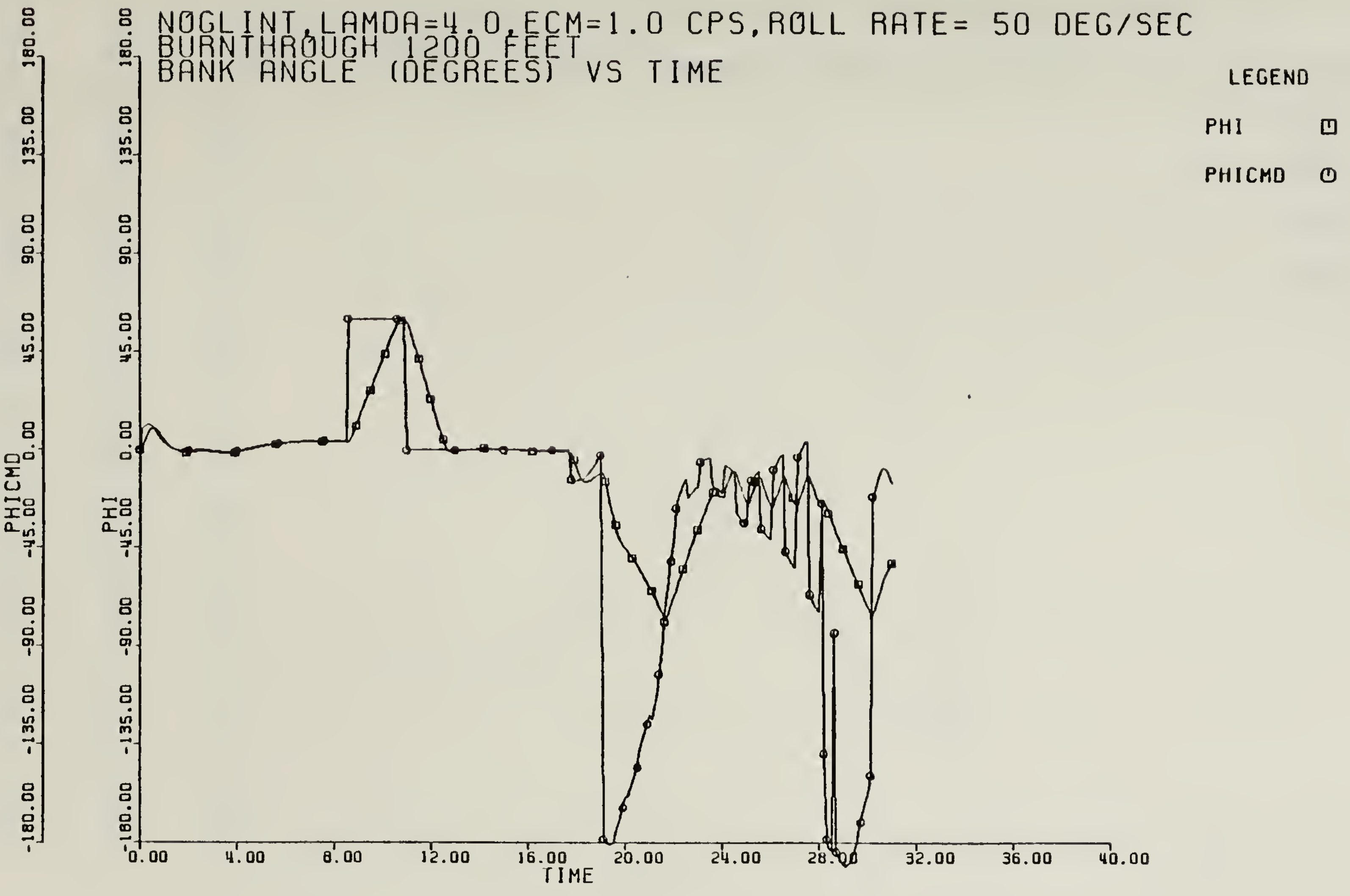


Figure 5-3b Baseline Response for ECM 1 CPS, Roll Rate Limit 50 deg/sec

(PHICMD, PHI vs TIME)

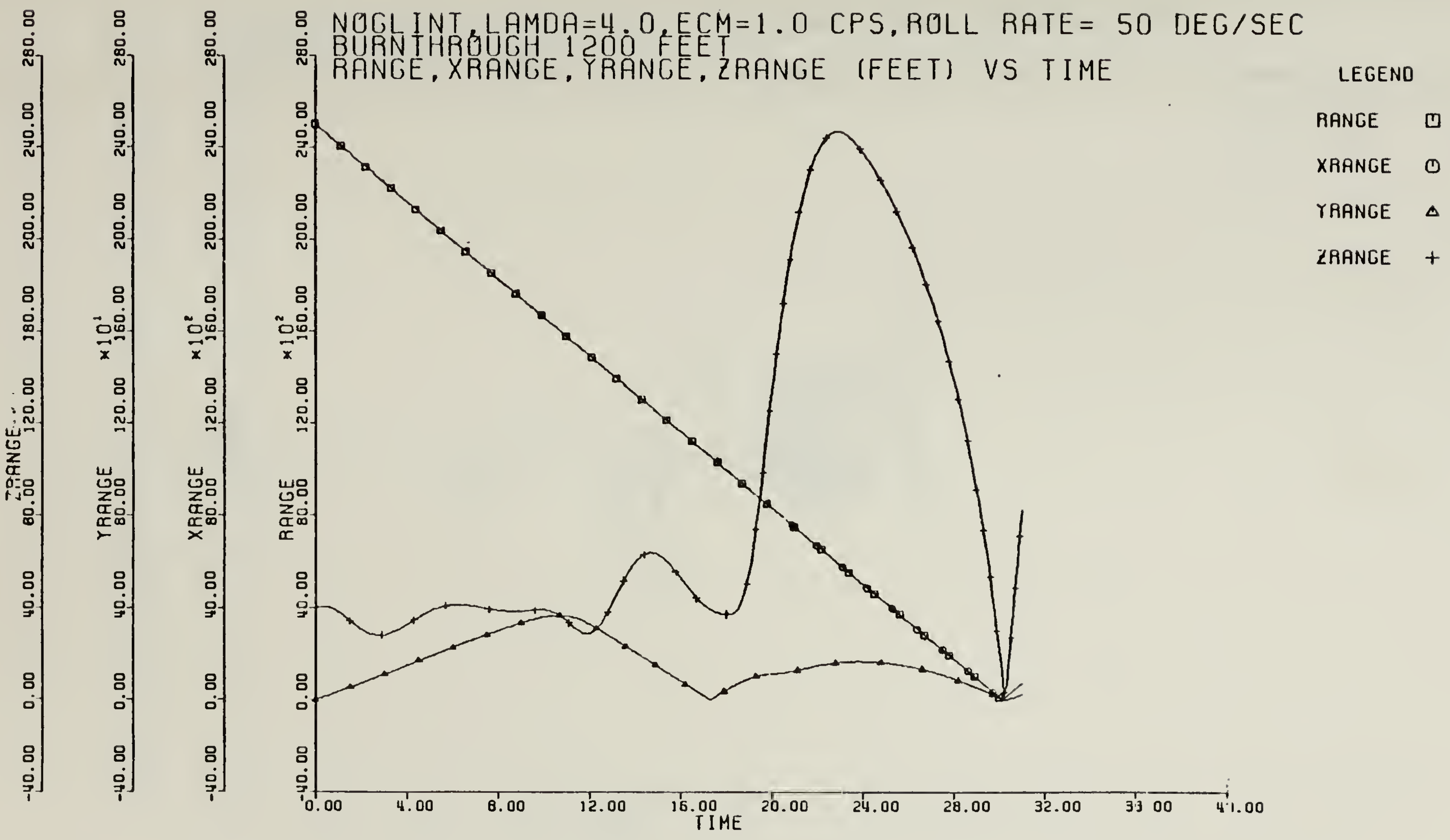


Figure 5-3c Baseline Response for ECM 1 CPS, Roll Rate Limit 50 deg/sec

(RANGE, XRANGE, YRANGE, ZRANGE vs TIME)

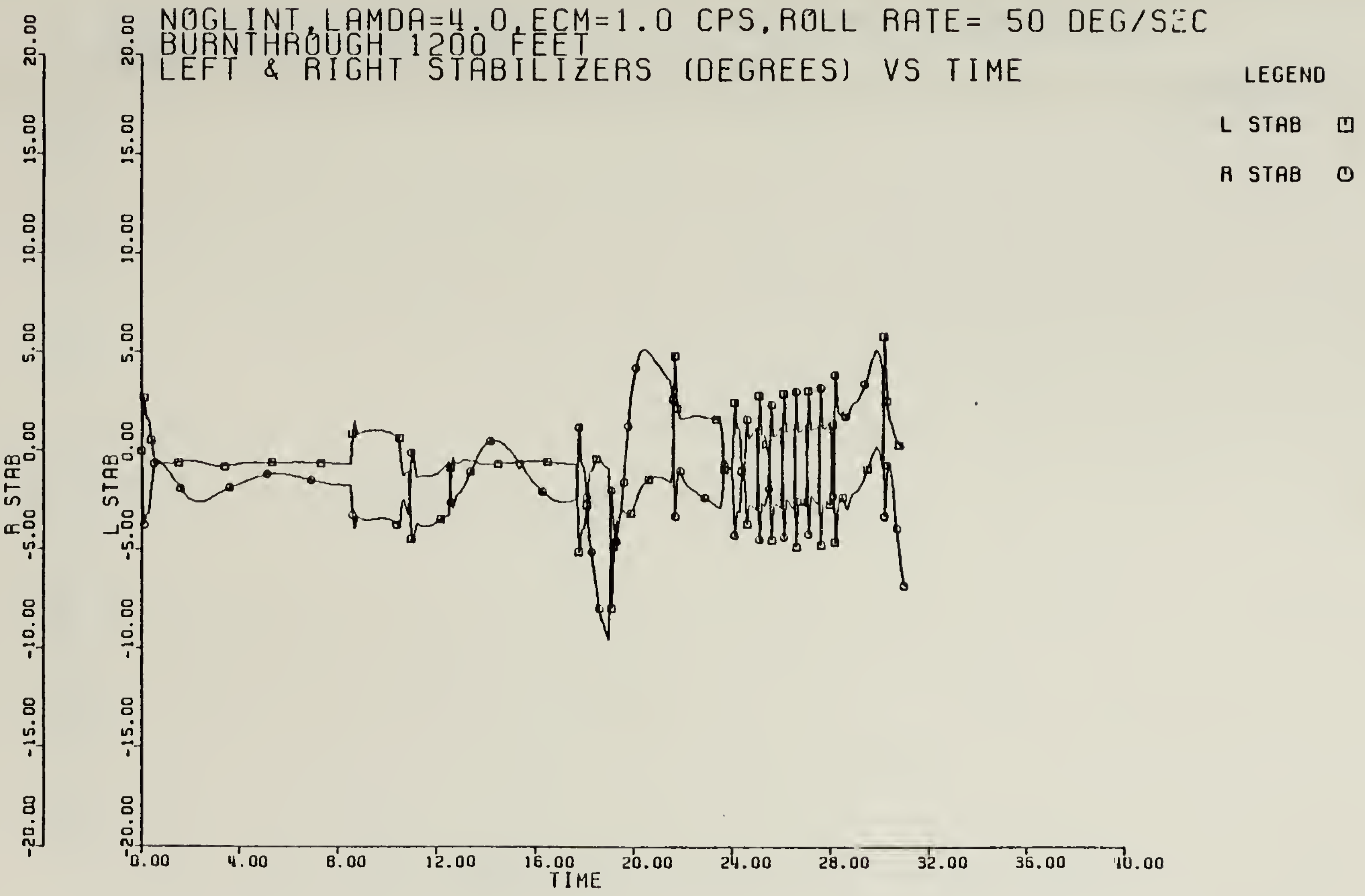


Figure 5-3d Baseline Response for ECM 1 CPS, Roll Rate Limit 50 deg/sec

(L STAB, R STAB vs TIME)

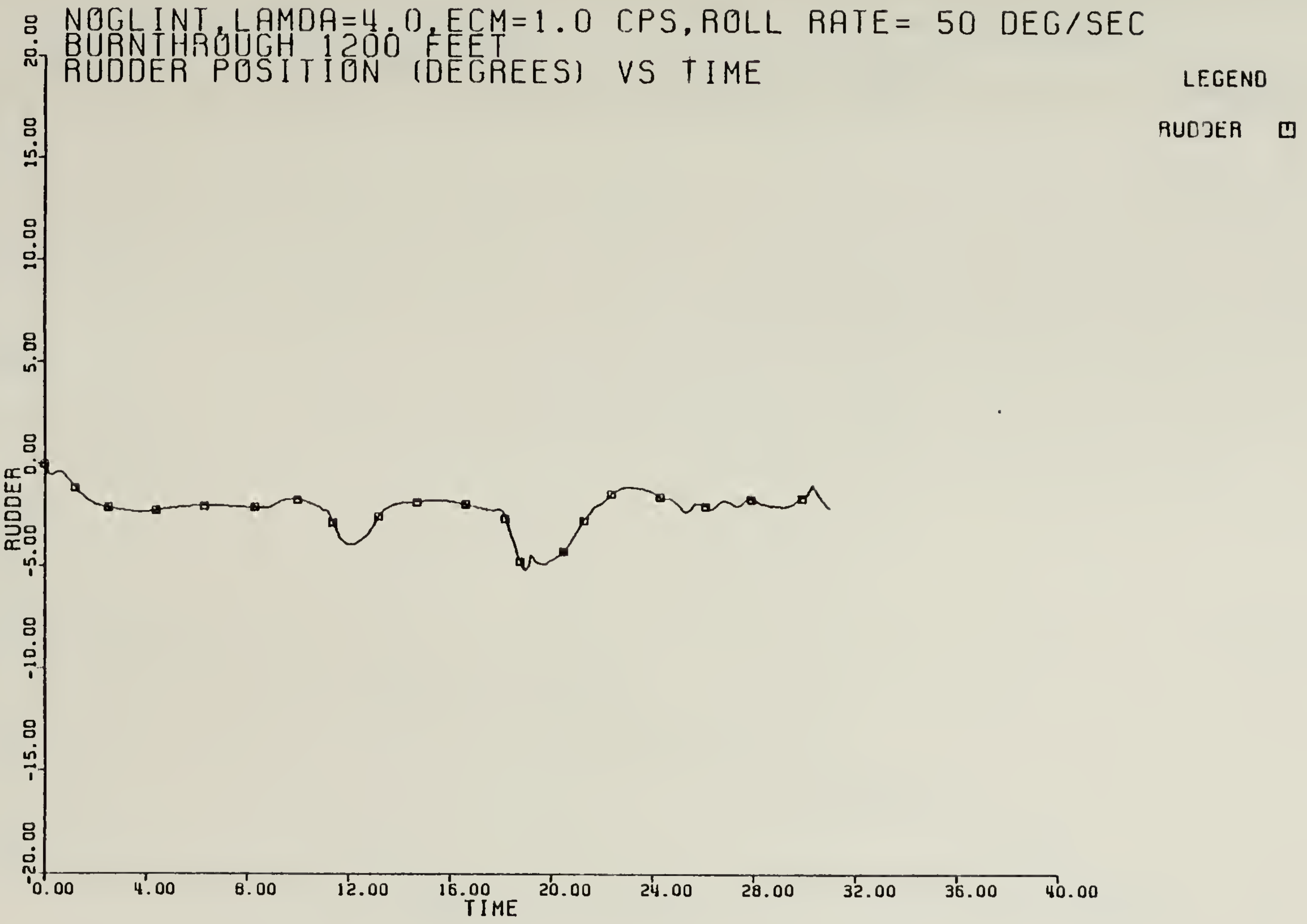


Figure 5-3e Baseline Response for ECM 1 CPS, Roll Rate Limit 50 deg/sec

(RUDDER vs TIME)

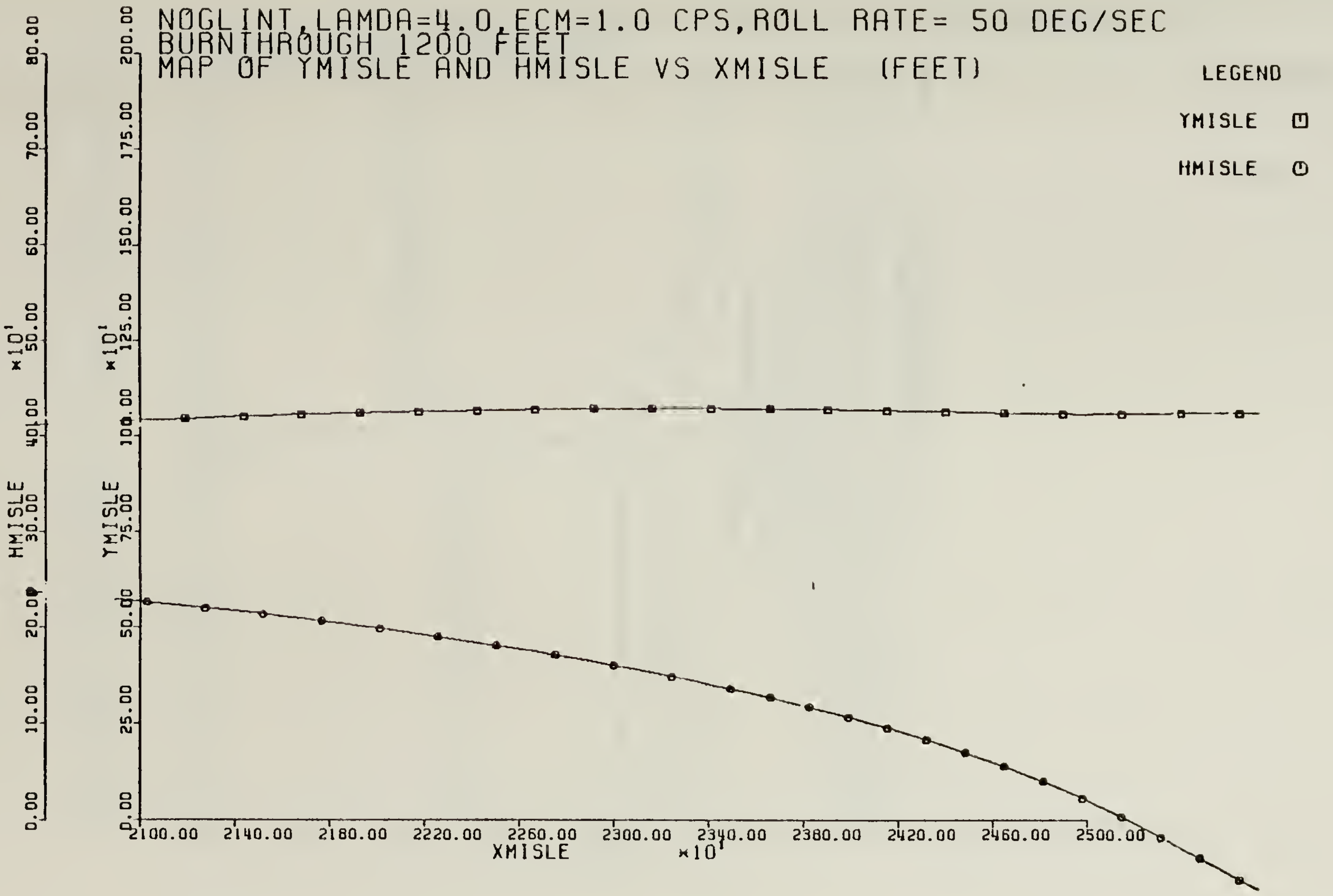


Figure 5-3f Baseline Response for ECM 1 CPS, Roll Rate Limit 50 deg/sec

(YMISLE, HMISLE vs XMISLE)

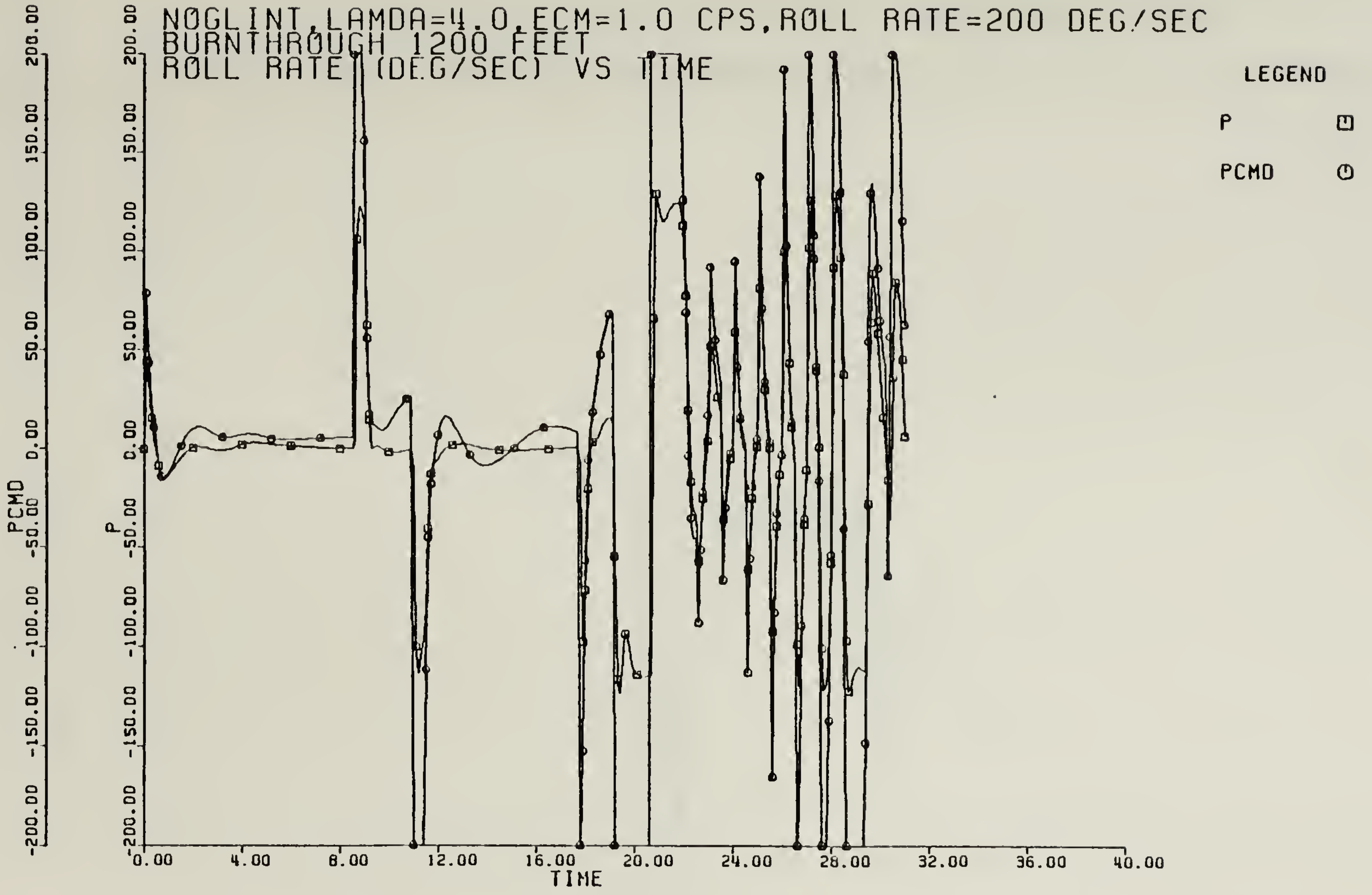


Figure 5-4a Baseline Response for ECM 1 CPS, Roll Rate Limit 200 deg/sec

PCMD,P vs TIME)

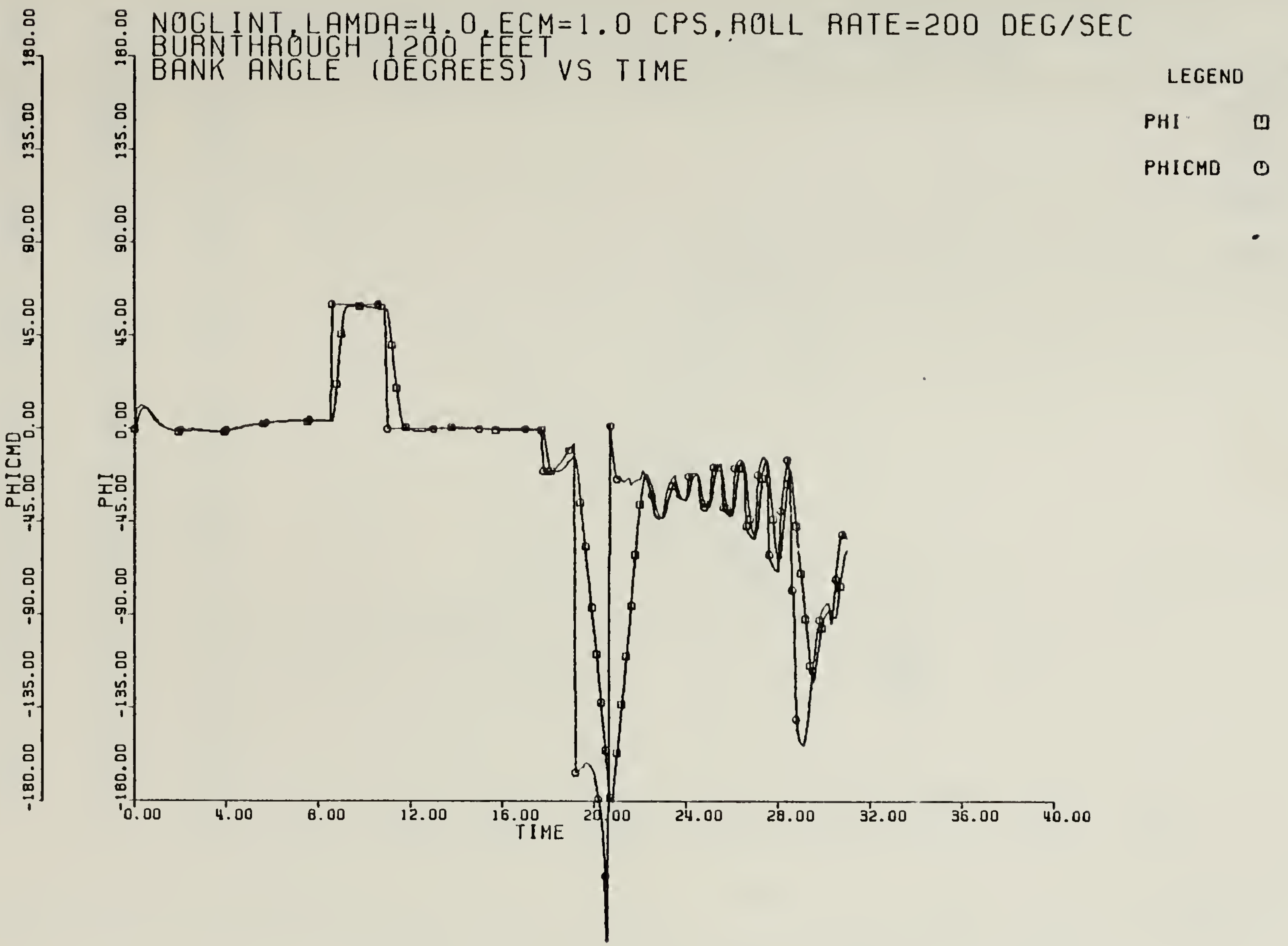


Figure 5-4b Baseline Response for ECM 1 CPS, Roll Rate Limit 200 deg/sec
(PHICMD, PHI vs TIME)

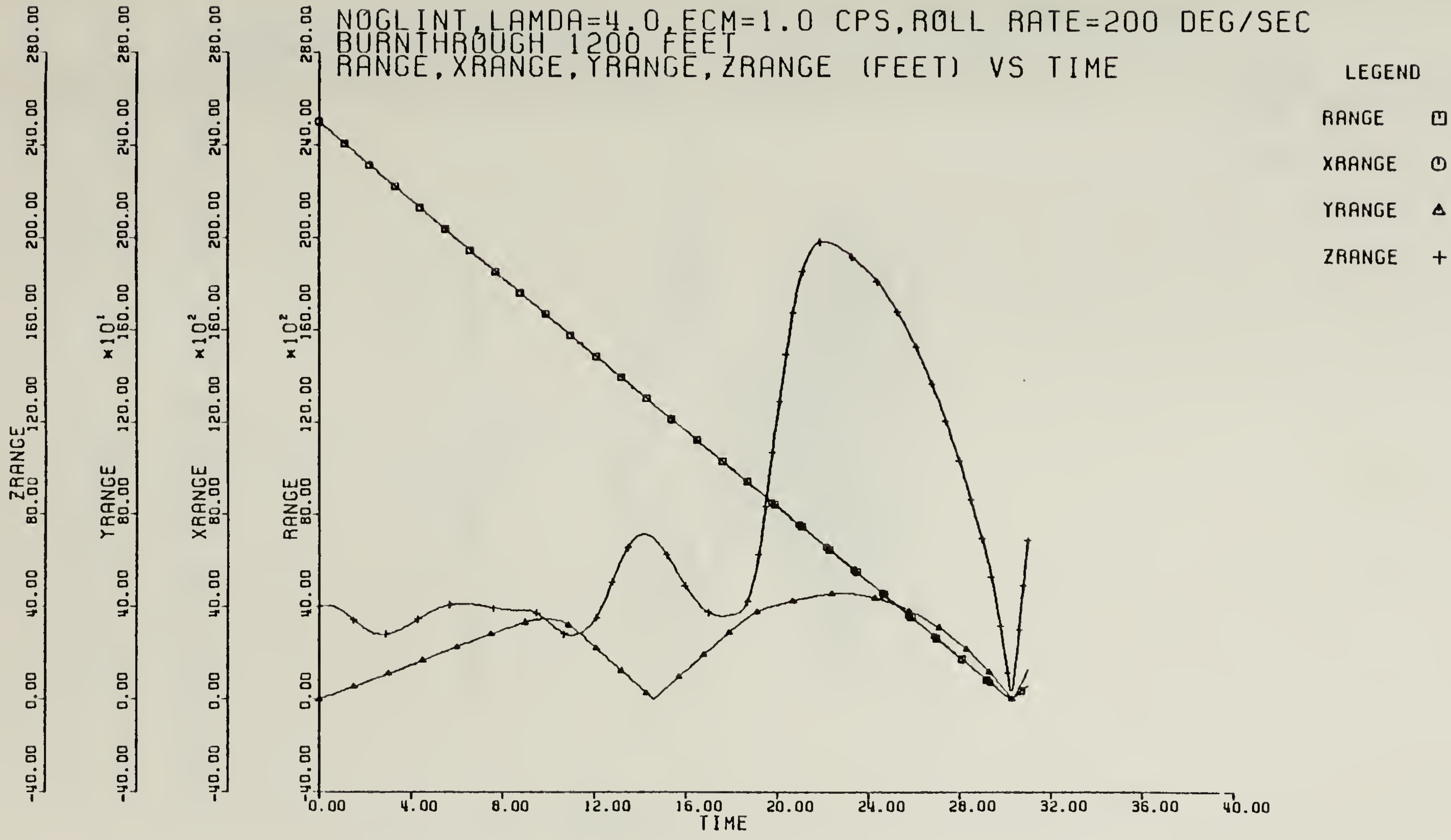


Figure 5-4c Baseline Response for ECM 1 CPS, Roll Rate Limit 200 deg/sec

(RANGE, XRANGE, YRANGE, ZRANGE vs TIME)

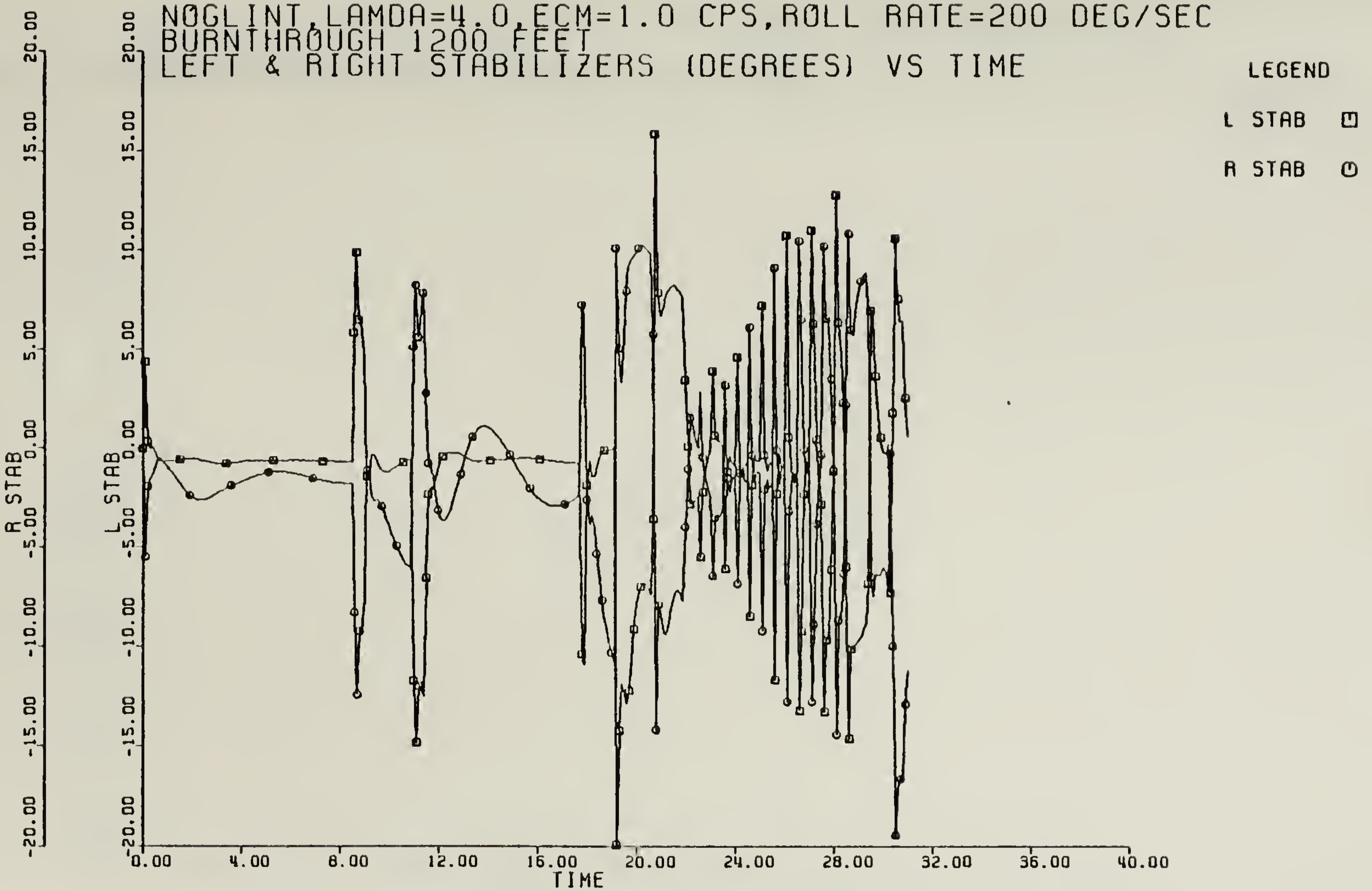


Figure 5-4d Baseline Response for ECM 1 CPS, Roll Rate Limit 200 deg/sec

(L STAB, R STAB vs TIME)

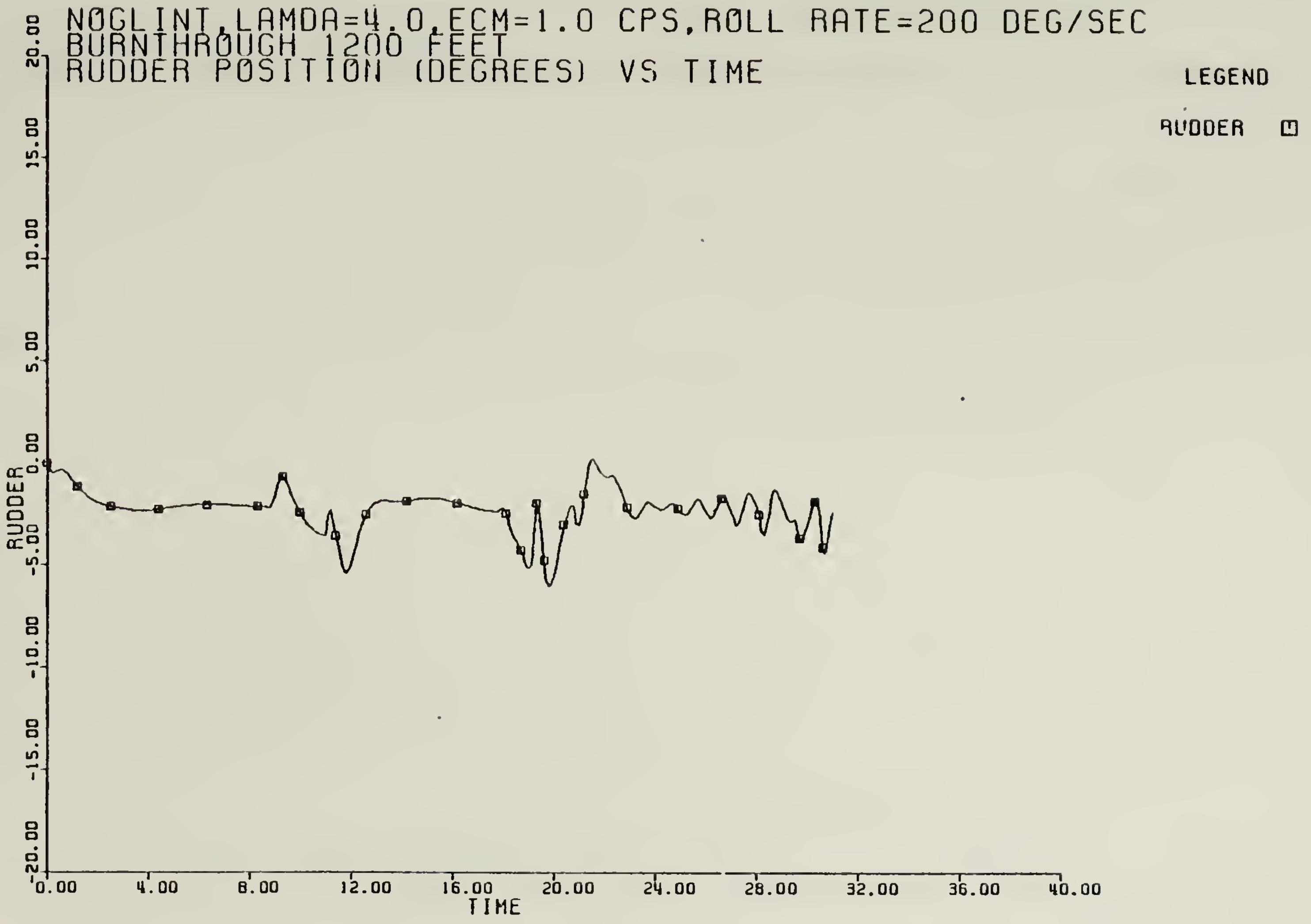


Figure 5-4e Baseline Response for ECM 1 CPS, Roll Rate Limit 200 deg/sec

(RUDDER vs TIME)

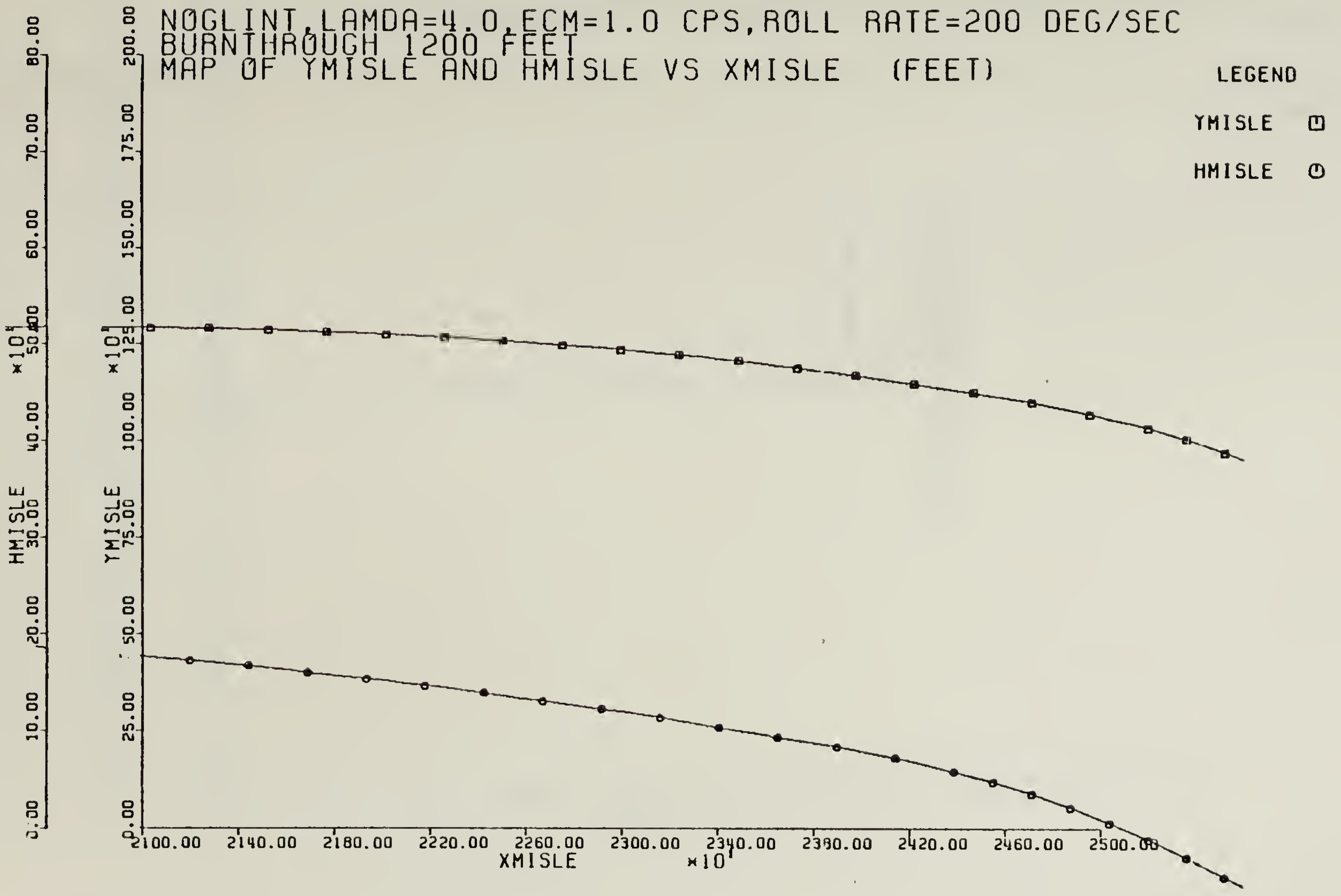


Figure 5-4f Baseline Response for ECM 1 CPS, Roll Rate Limit 200 deg/sec

(YMISLE, HMISLE vs XMISLE)

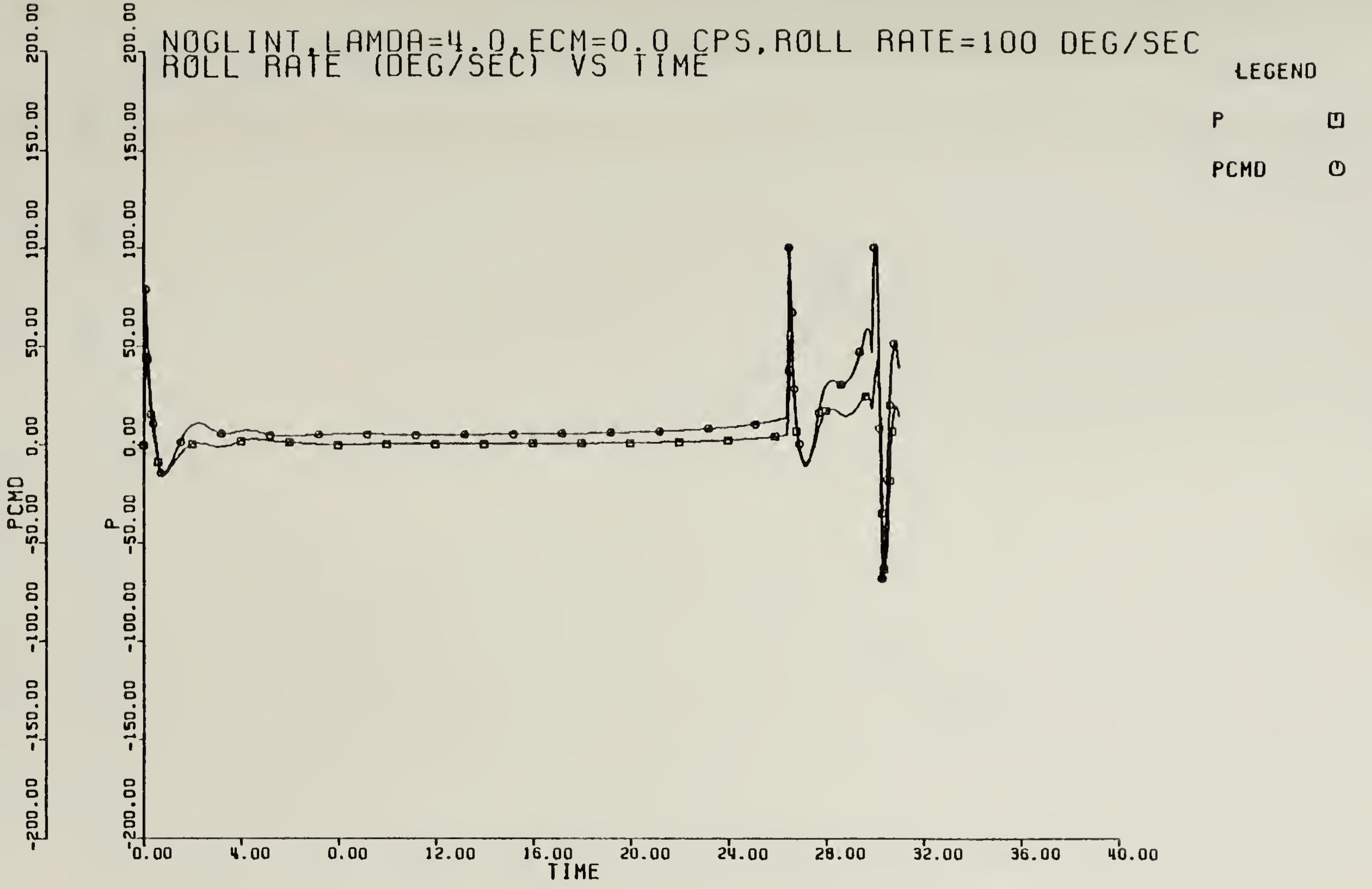


Figure 5-5a Sea Skimmer Response for No ECM, Roll Rate Limit 100 deg/sec

(PCMD, P vs TIME)

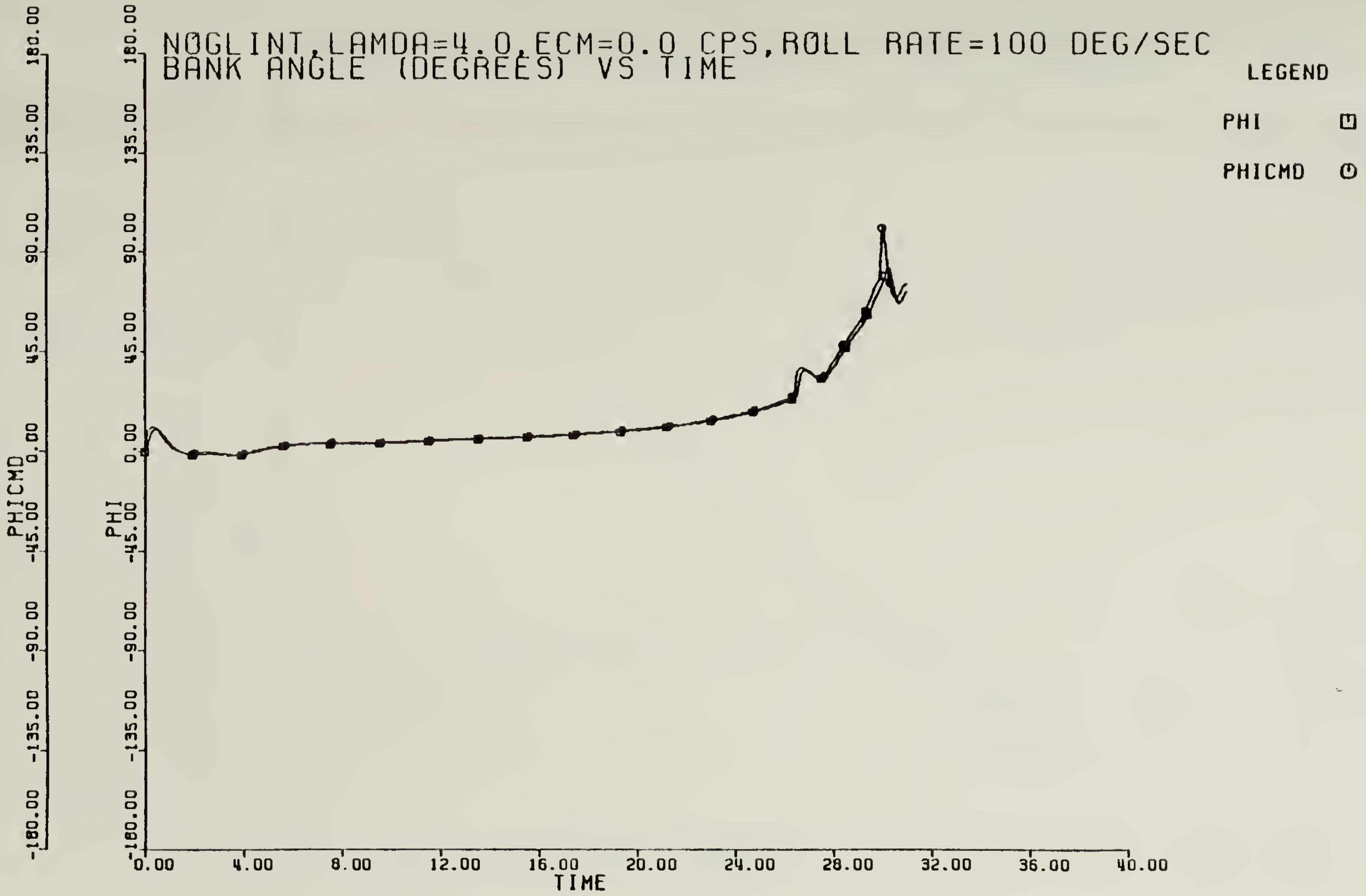


Figure 5-5b Sea Skimmer Response for No ECM, Roll Rate Limit 100 deg/sec

(PHICMD, PHI vs TIME)

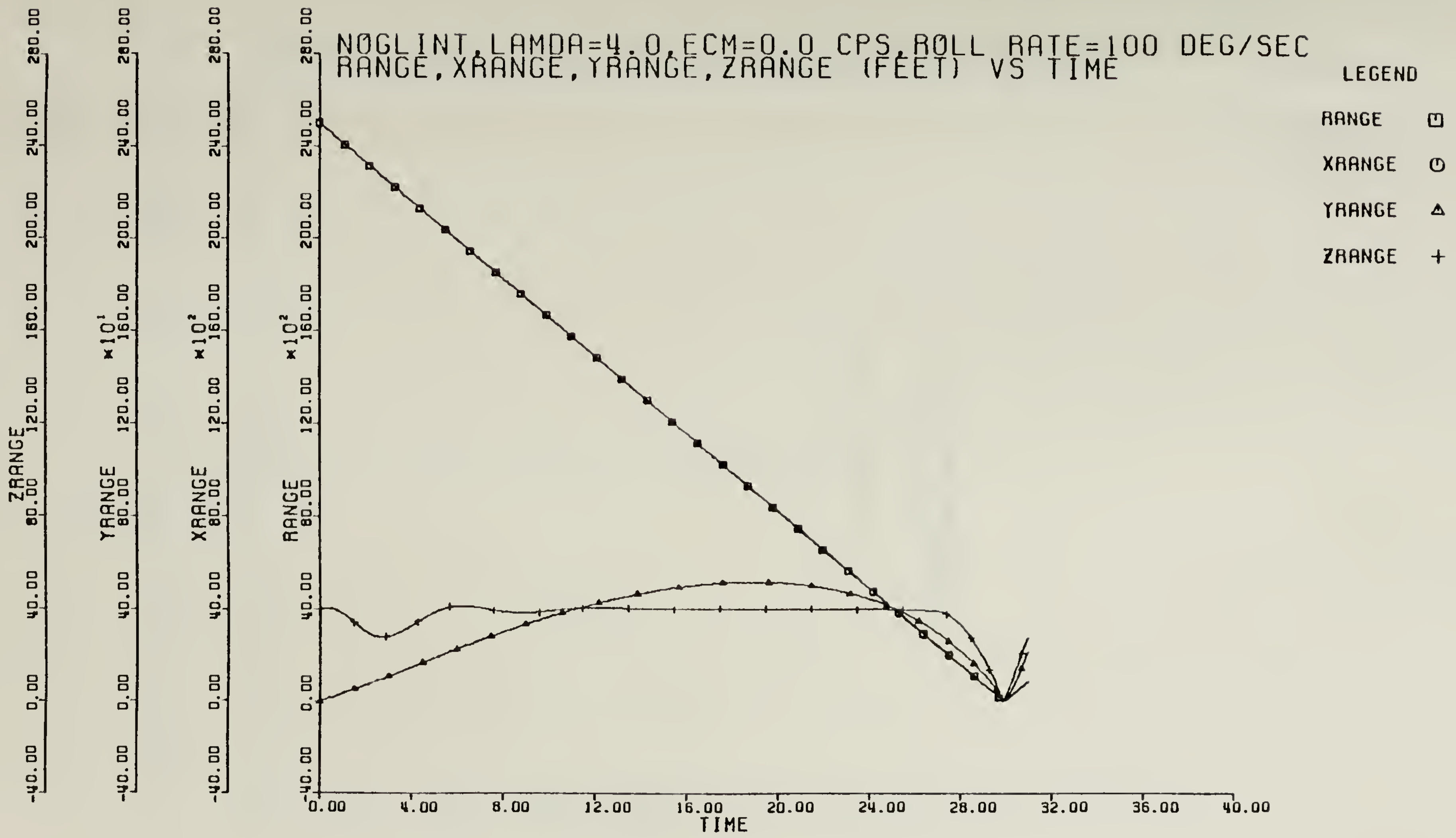


Figure 5-5c Sea Skimmer Response for No ECM, Roll Rate Limit 100 deg/sec

(RANGE, XRANGE, YRANGE, ZRANGE vs TIME)

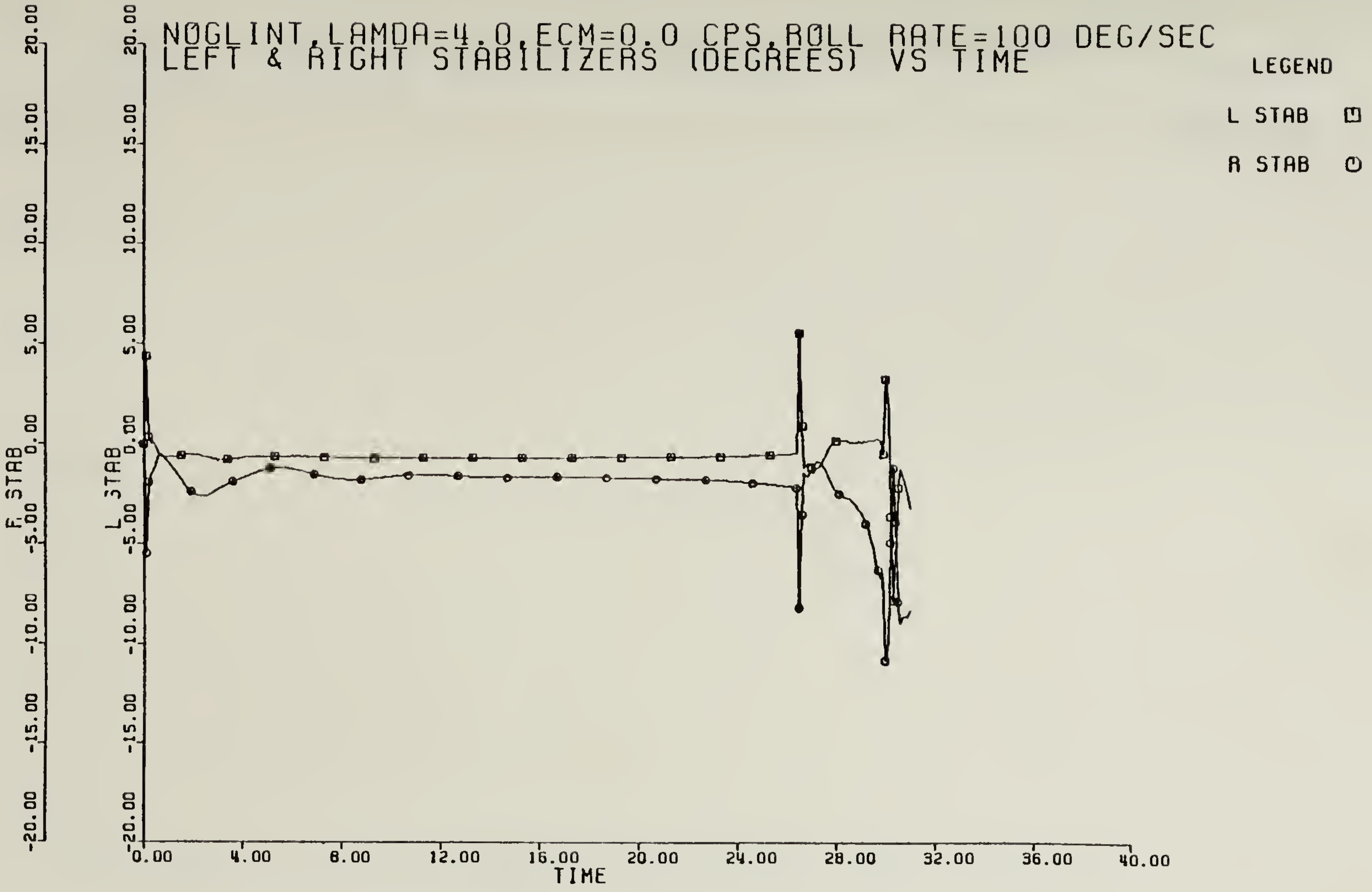


Figure 5-5d Sea Skimmer Response for No ECM, Roll Rate Limit 100 deg/sec

(L STAB, R STAB vs TIME)

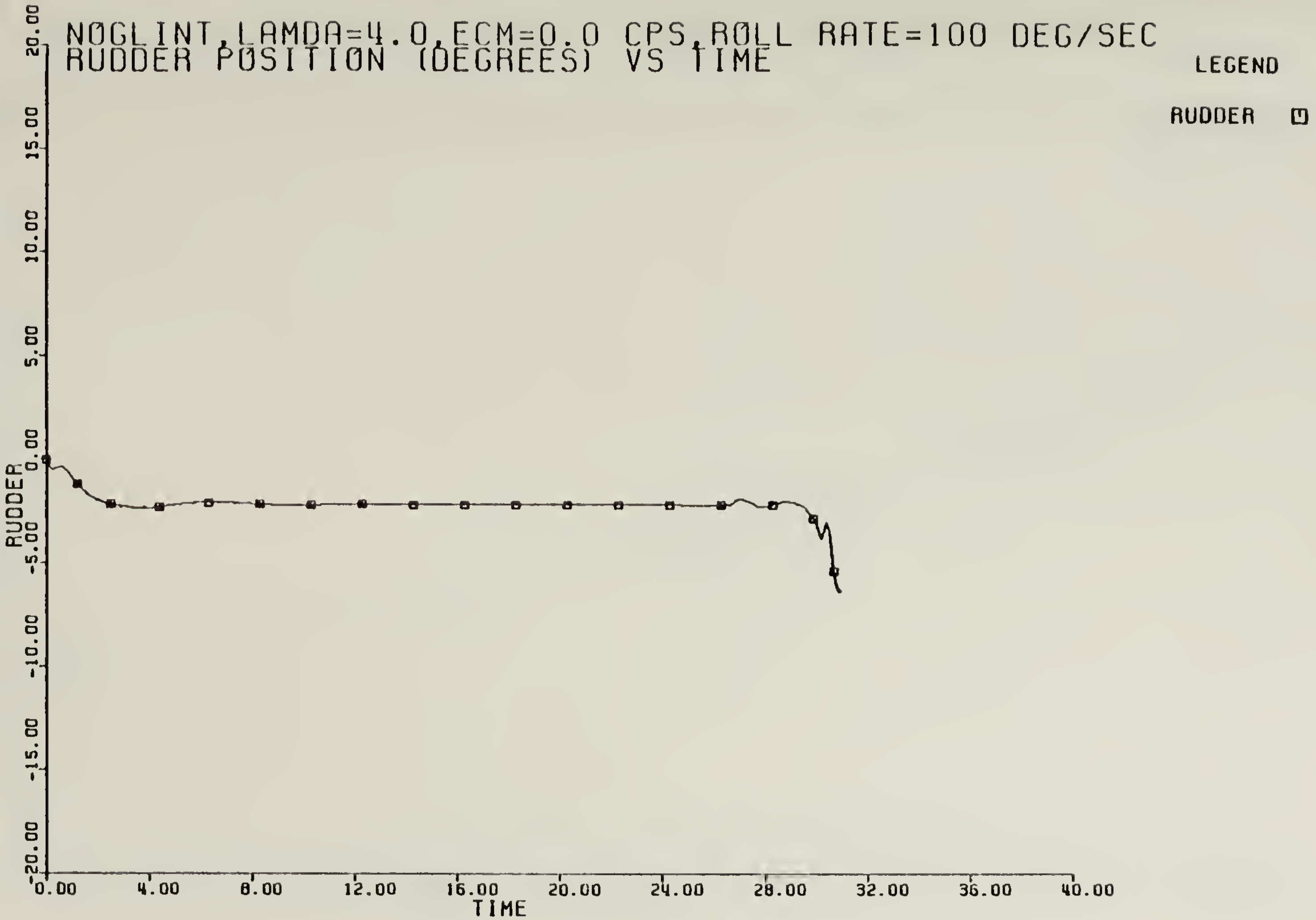


Figure 5-5e Sea Skimmer Response for No ECM, Roll Rate Limit 100 deg/sec

RUDDER vs TIME)

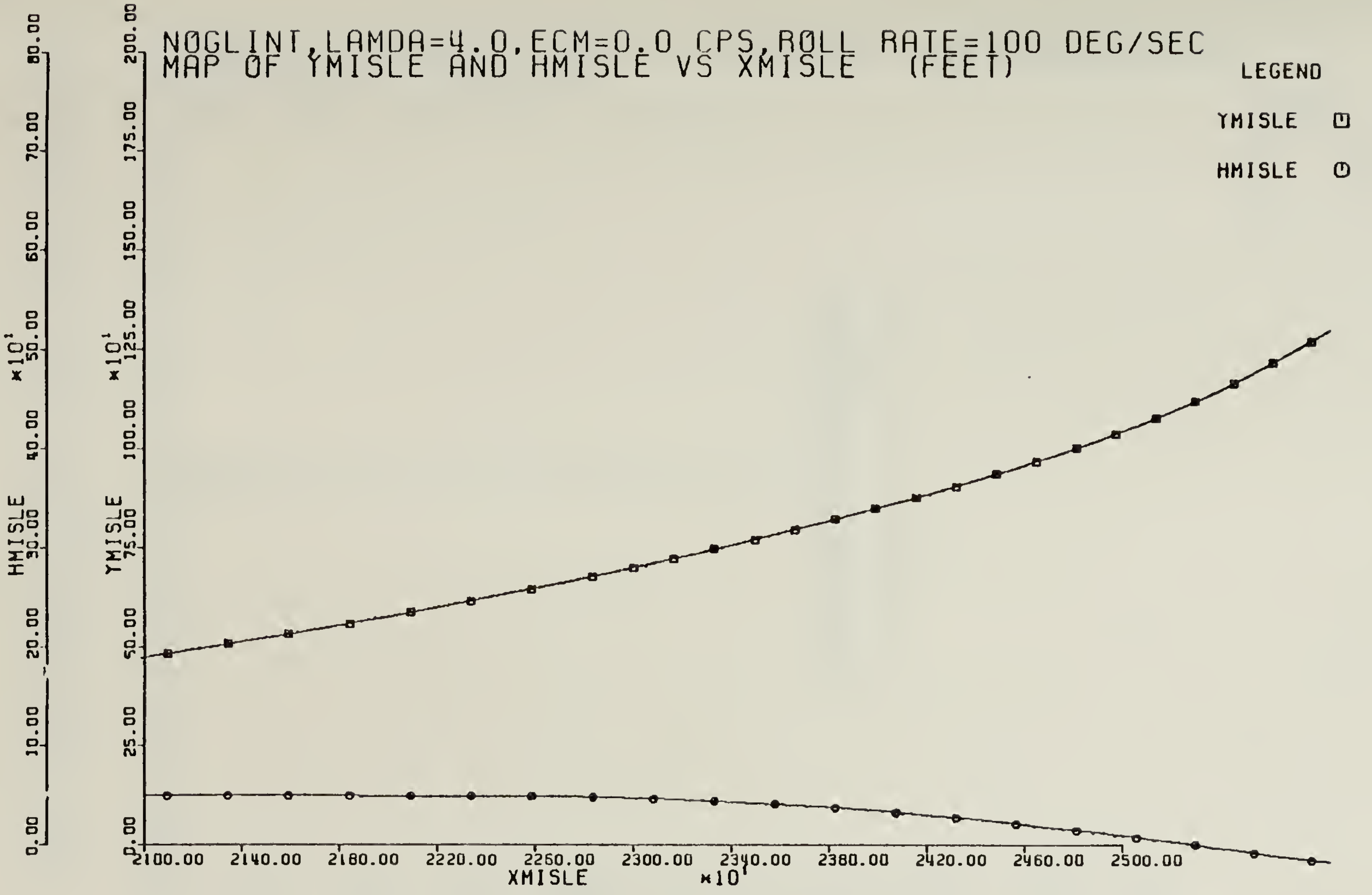


Figure 5-5f Sea Skimmer Response for No ECM, Roll Rate Limit 100 deg/sec

YMISLE, HMISLE vs XMISLE)

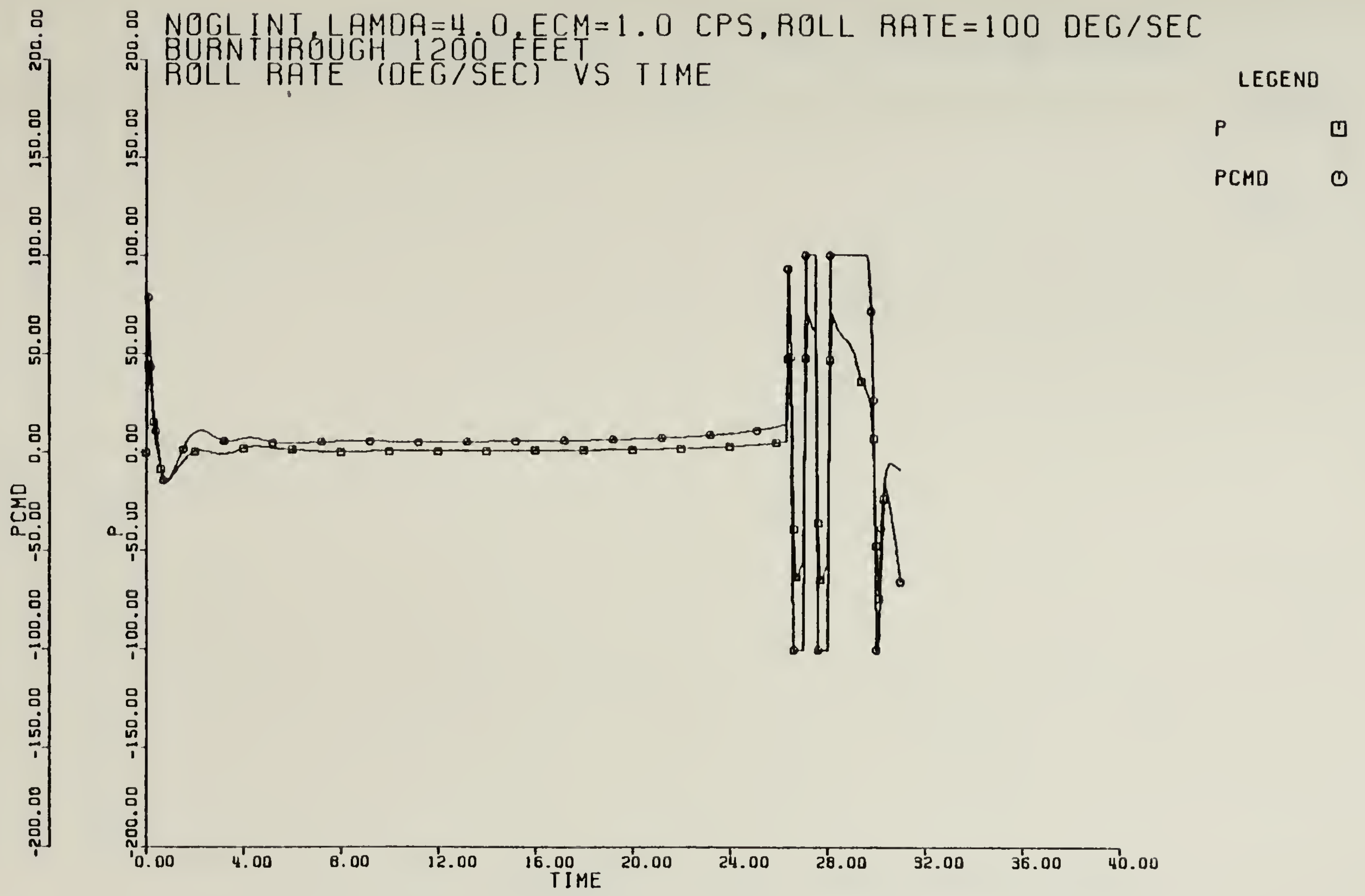


Figure 5-6a Sea Skimmer Response for ECM 1 CPS, Roll Rate Limit 100 deg/sec

(PCMD, P vs TIME)

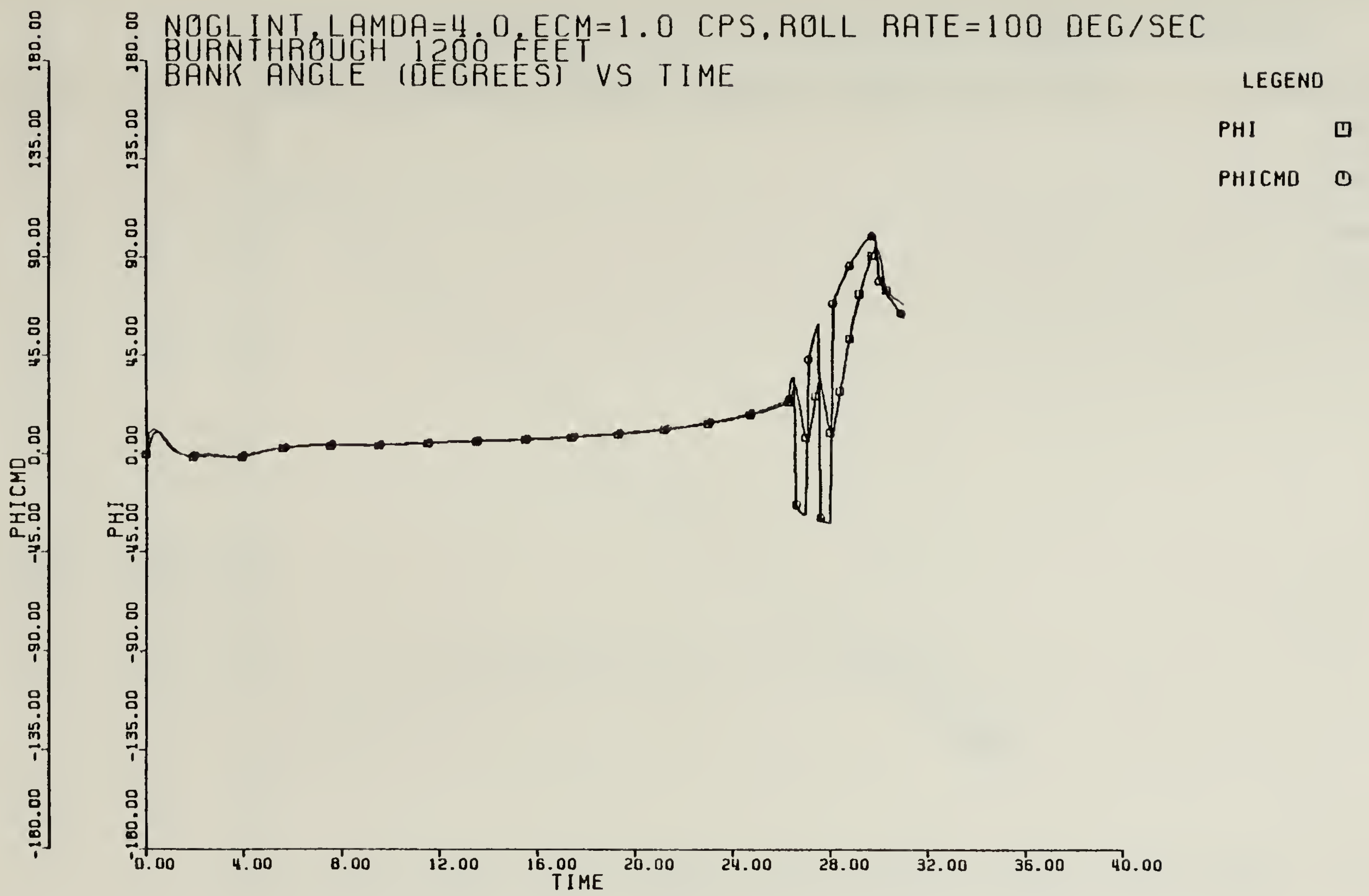


Figure 5-6b Sea Skimmer Response for ECM 1 CPS, Roll Rate Limit 100 deg/sec

(PHICMD, PHI vs TIME)

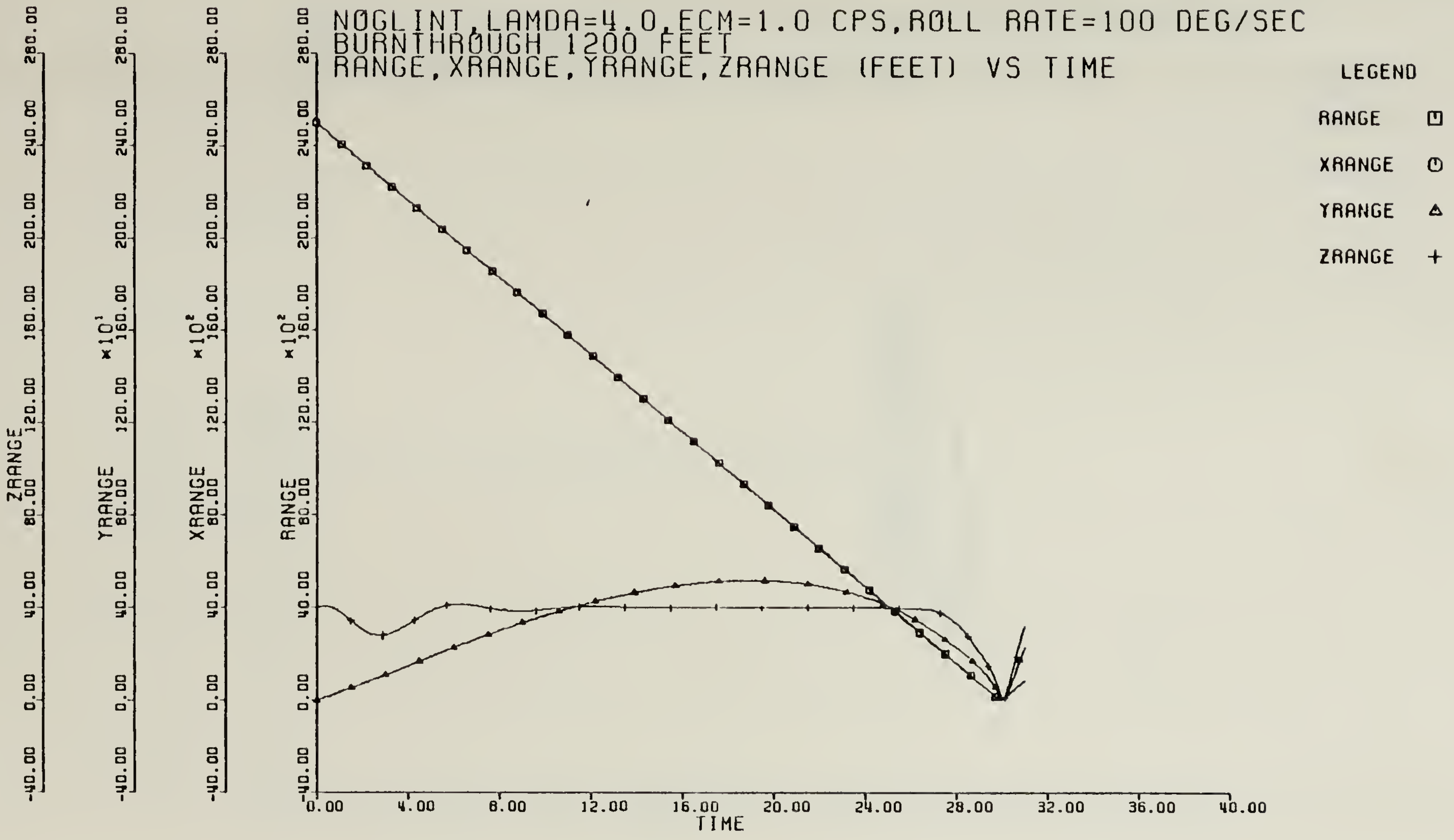


Figure 5-6c Sea Skimmer Response for ECM 1 CPS, Roll Rate Limit 100 deg/sec

(RANGE, XRANGE, YRANGE, ZRANGE vs TIME)

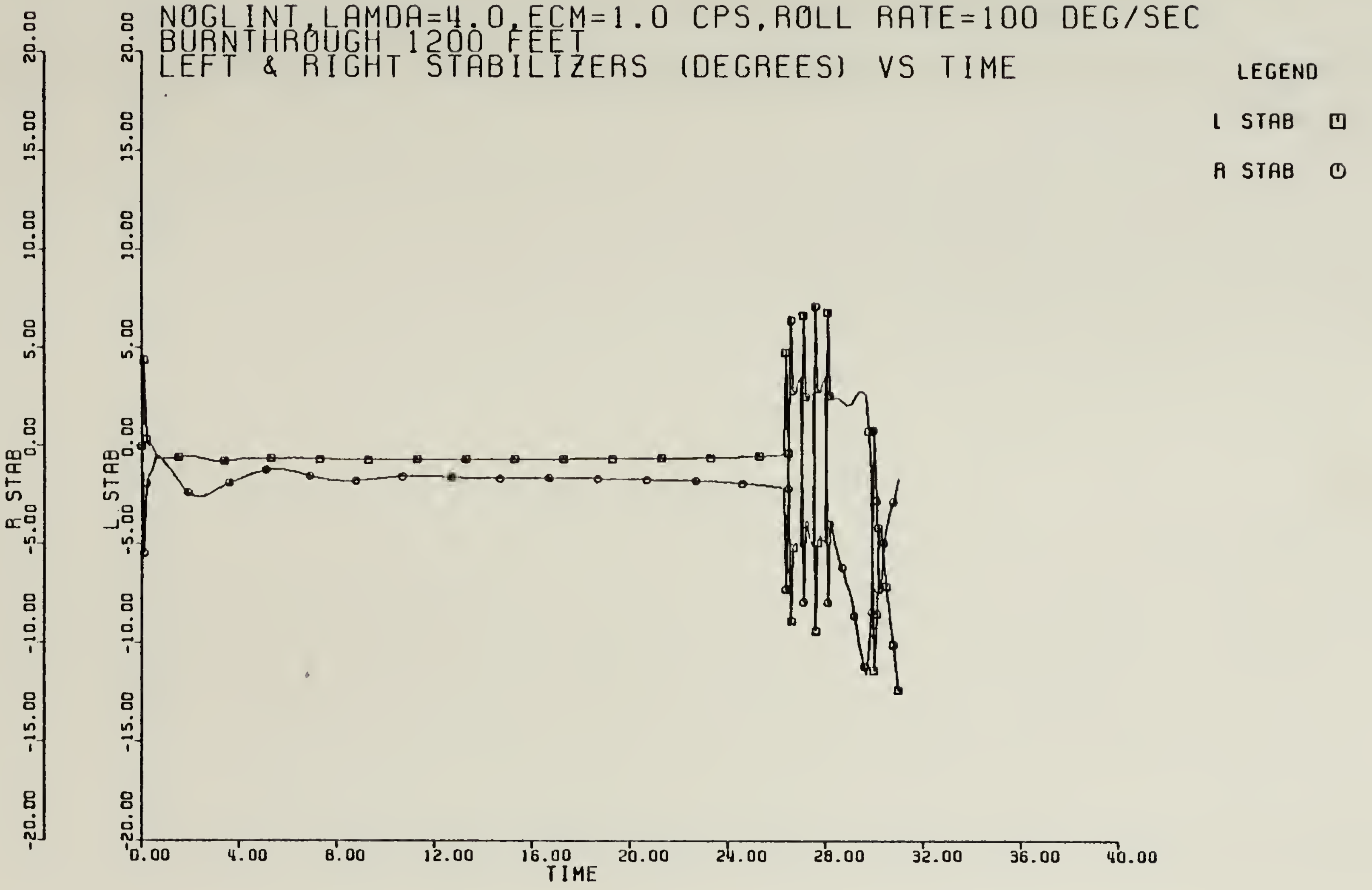


Figure 5-6d Sea Skimmer Response for ECM 1 CPS, Roll rate Limit 100 deg/sec

(L STAB, R STAB vs TIME)

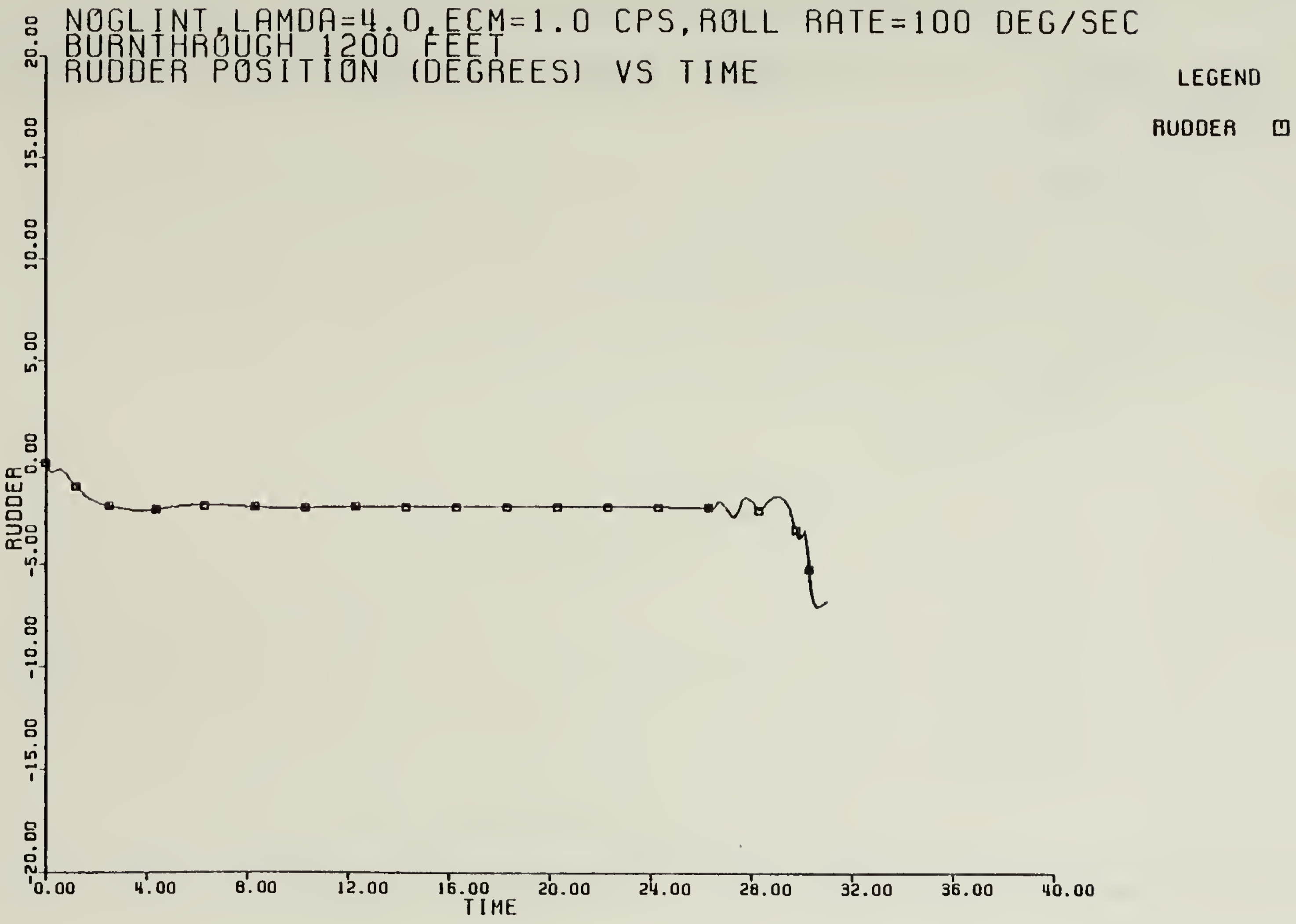


Figure 5-6e Sea Skimmer Response for ECM 1 CPS, Roll Rate Limit 100 deg/sec

(RUDDER vs TIME)

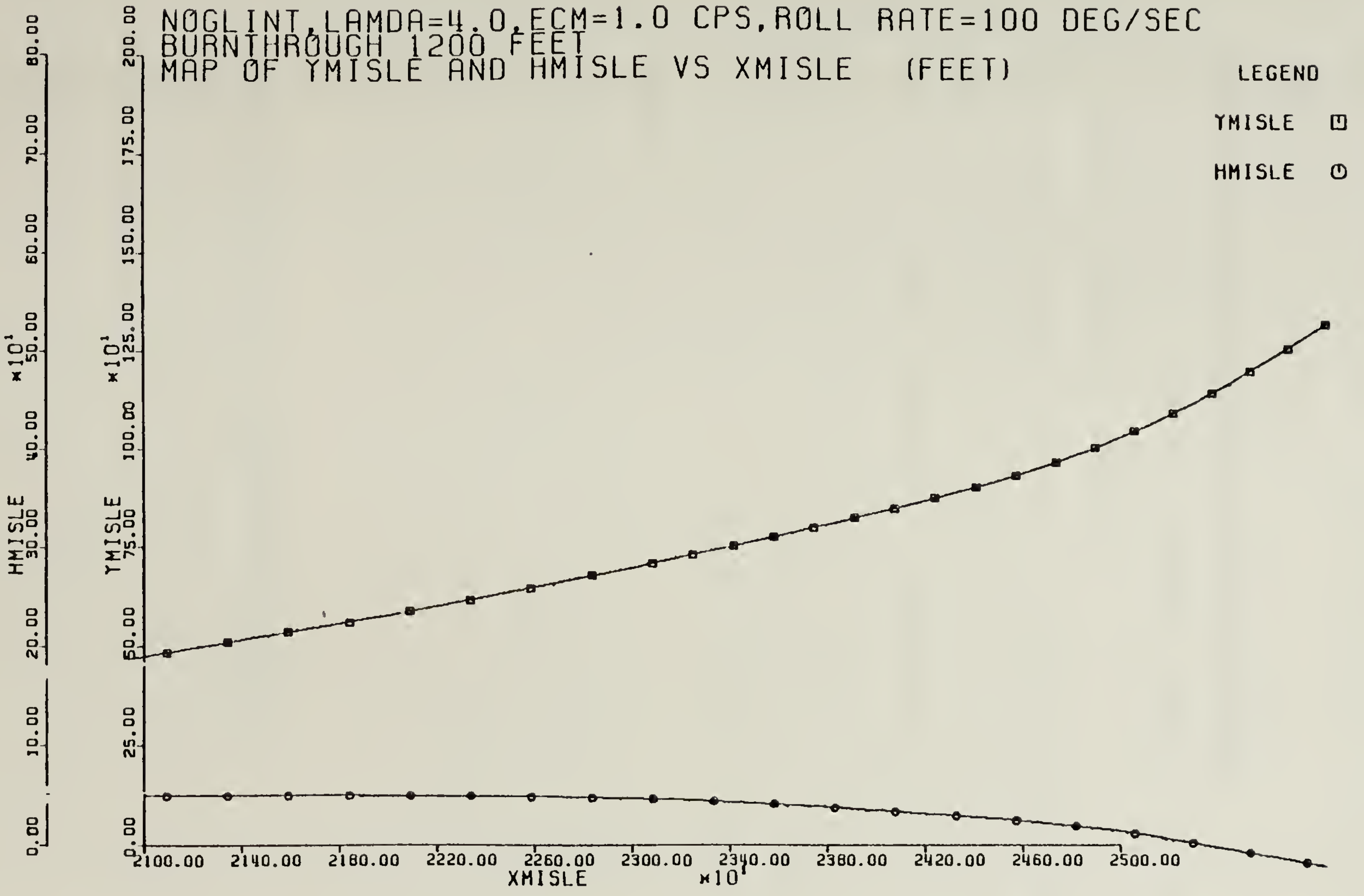


Figure 5-6f Sea Skimmer Response for ECM 1 CPS, Roll Rate Limit 100 deg/sec

(YMISLE, HMISLE vs XMISLE)

miss distance remains high for all burn through ranges out to 2000 feet. But, for the remaining blinking frequencies and burn through ranges the miss distances improve significantly for increasing roll rate limits. A miss distance of 7.9 feet for a burn through range of 800 feet and 2 Hertz blinking frequency is excellent.

2. Analysis of Sea Skimmer Scheme Results

The results for the sea skimmer scheme are quite different than the baseline scheme.

Burn through range seems to be the single most controlling variable. Miss distances for a burn through range of 1500 feet are marginally satisfactory for all roll rate limits and ECM blinking rates. However, at a burn through range of 2000 feet, miss distances for varying roll rate limits and ECM blinking frequencies are extremely low and considered quite good.

Varying the ECM blinking rate produces little effect on the miss distances. However, a unique roll rate limit of 100 degrees per second produces miss distances double the miss distances for roll rate limits of 50 or 200 degrees per second.

3. Analysis of Glint Simulation Results

Figure 5-7 shows the random introduction of glint in the target position and line of sight rate. The miss distance for the run in this figure is 15 feet, but analysis from other runs show that glint increases the miss distance 30 to 50 percent.

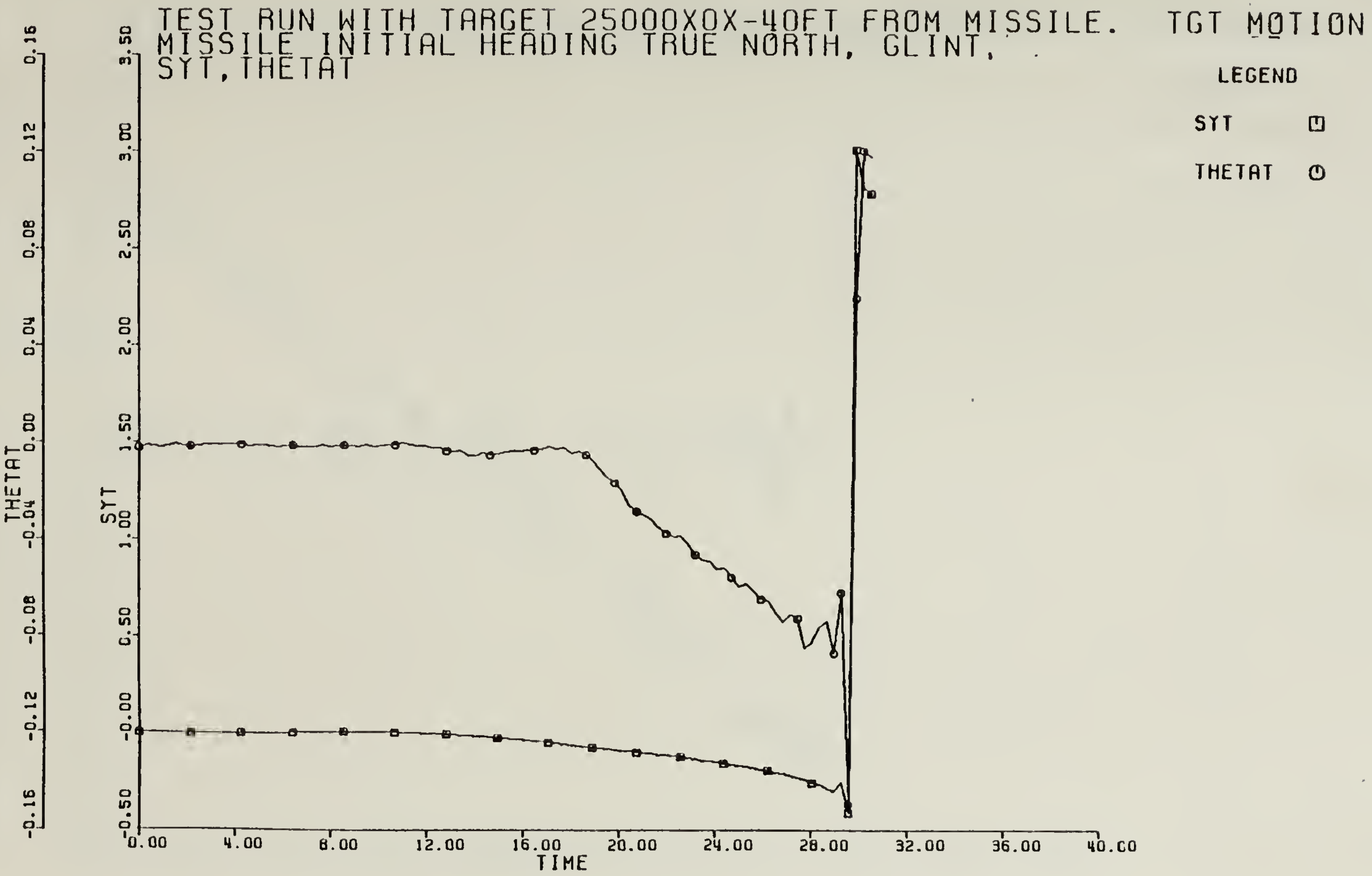


Figure 5-7a Baseline Response with Glint
(SYT, THEATAT vs TIME)

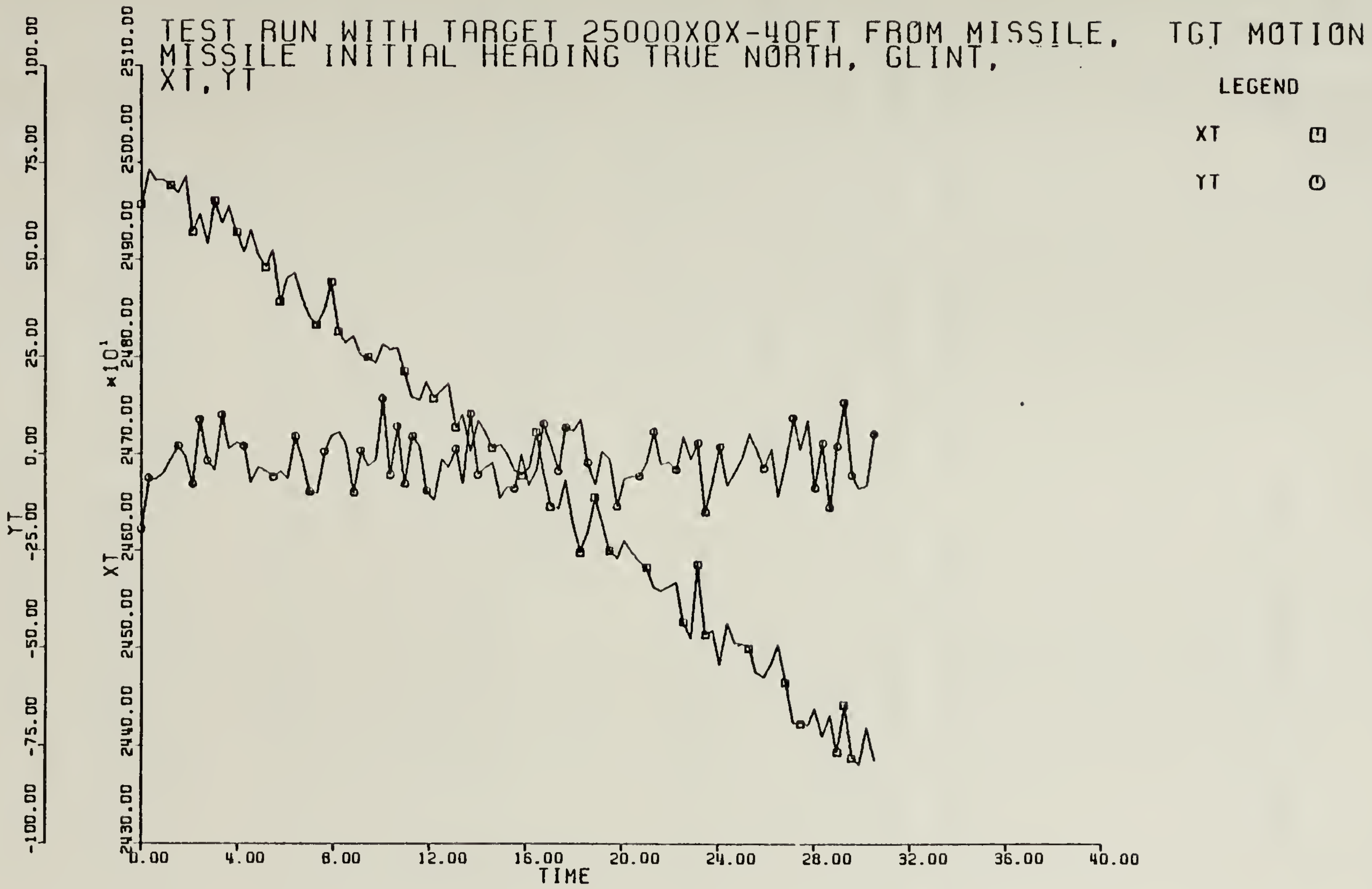


Figure 5-7b Baseline Response with Glint
(XT, YT vs Time)

4. Proportional Navigation Ratio Selection

The following matrix shows the result of miss distance in a no ECM environment for varying proportional navigation constant (PN).

PN	Miss Distance (feet)
3	10.6
3.5	6.9
4	4.4
4.5	3.2

Although a proportional navigation constant (PN) of 4.5 results in the smallest miss distance excessive over shoot to step inputs results in this proportional navigation constant as being an unsatisfactory choice. A PN of 4.0 was chosen based upon satisfactory system responses and the small miss distance achieved.

C. CONCLUSIONS AND RECOMMENDATIONS

Based upon the results of this study it can be concluded that miss distance is a function of roll rate limit, ECM blinking rate, burn through range, and the guidance scheme chosen. The guidance scheme chosen is most significant of these factors.

For the baseline guidance and control scheme, roll rate limit is the most significant variable affecting miss distance. One exception to this is the 0.5 Hertz blinking

rate set of runs which shows a miss distance improvement when roll rate is increased from 50 to 100 degrees per second, but yields poor miss distances for 200 degrees per second.

The most significant variable affecting miss distance for the sea-skimmer scheme is burn through range. Nevertheless, a 100-degree-per-second roll rate limit appears to be unacceptable at all burn through ranges simulated.

In summary, given that the target controls ECM blinking frequency and burn through range, the optimum selections are:

Baseline Scheme - Roll rate limit = 200 degrees per second

Sea-Skimmer - Roll rate limit = 50 or 200 degrees per second

The following additional studies are recommended:

a. Further modeling with glint.

b. Variation of the direction and magnitude of the ECM shift.

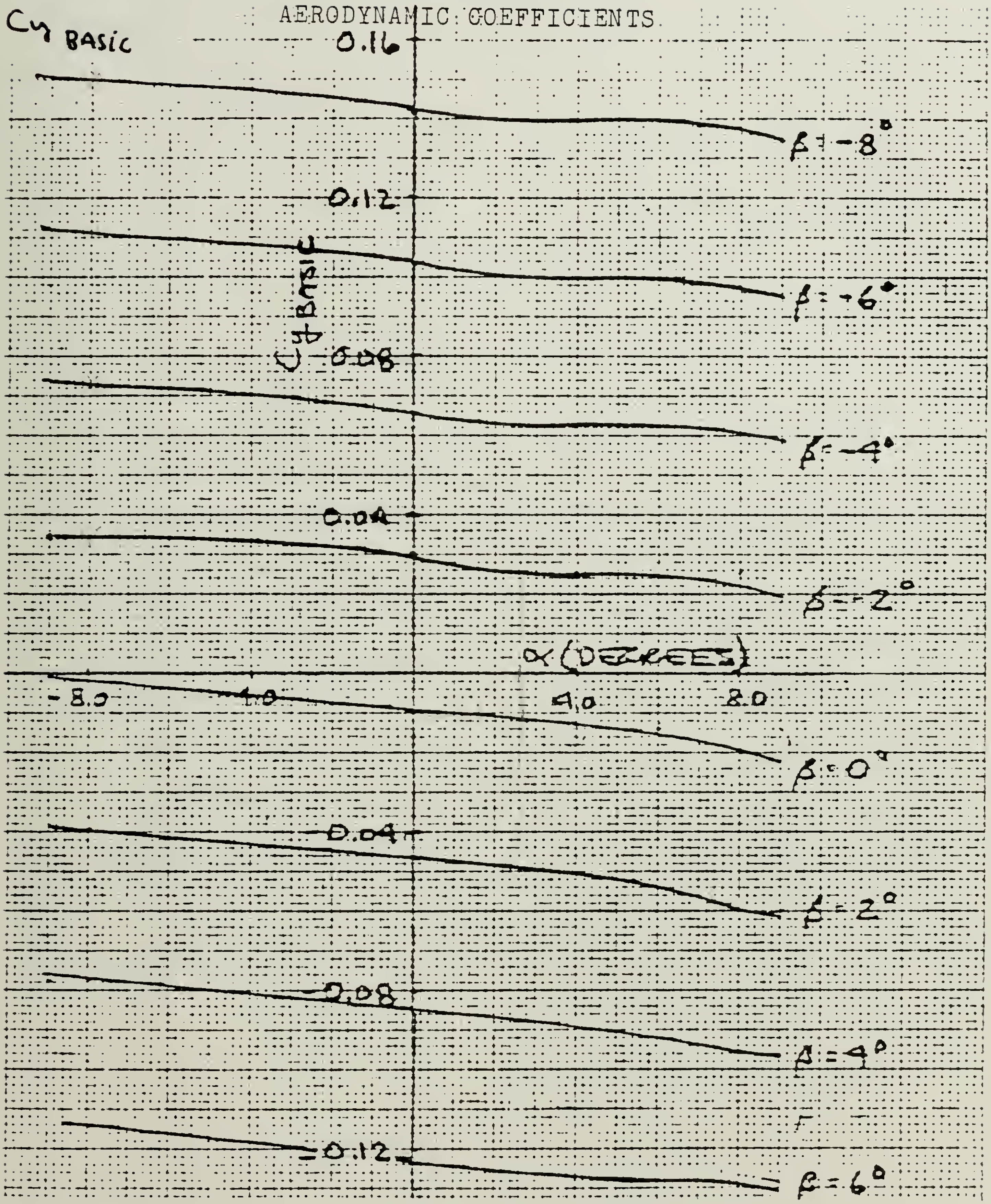
c. Alteration of the decision variable used in the simulation to switch phases from range to line of sight rate.

d. Variations in flight path geometry.

e. Comparison of control laws using skid-to-turn with control laws using bank-to-turn maneuvering.

APPENDIX A

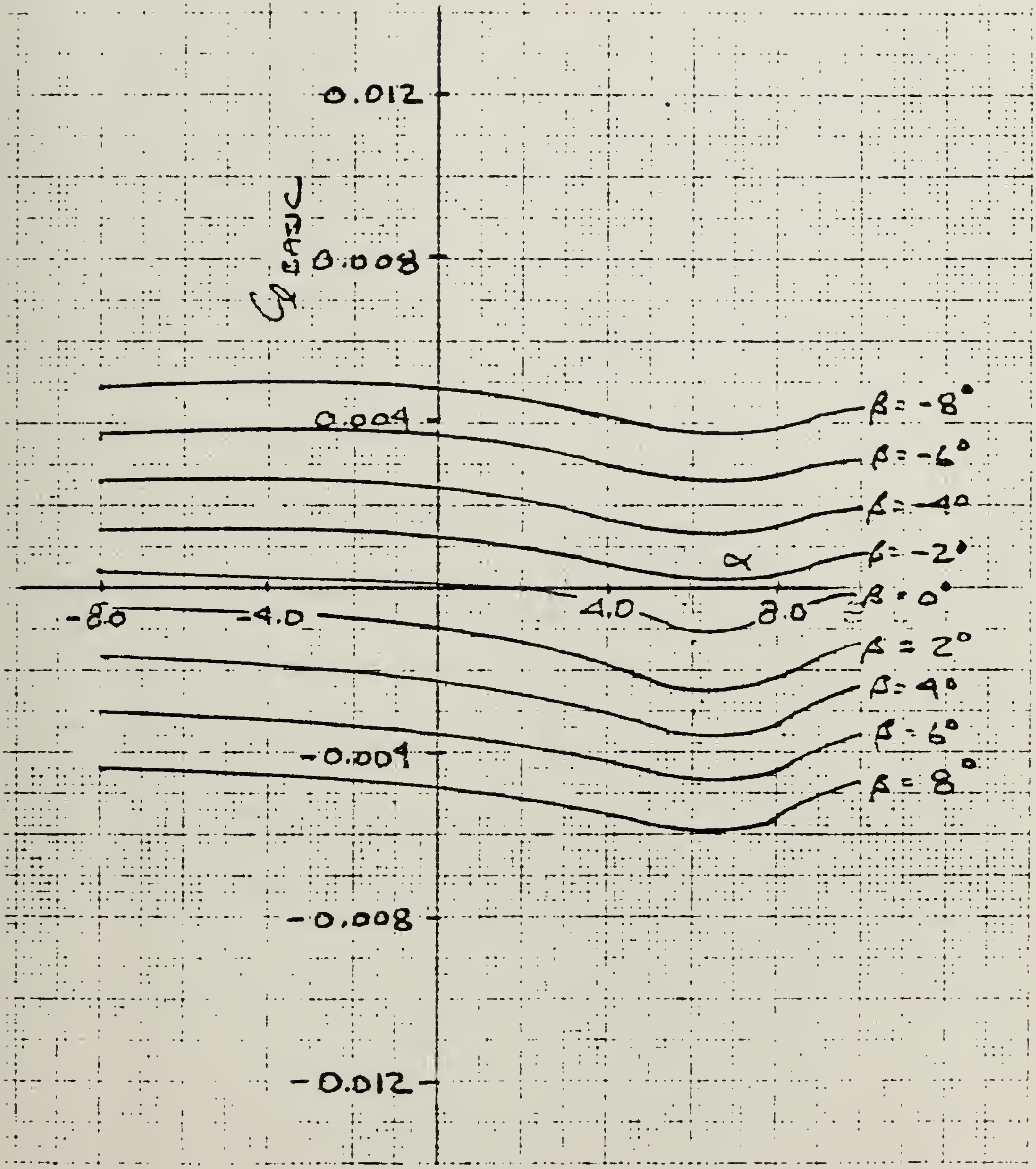
AERODYNAMIC COEFFICIENTS



Side Slip Characteristics

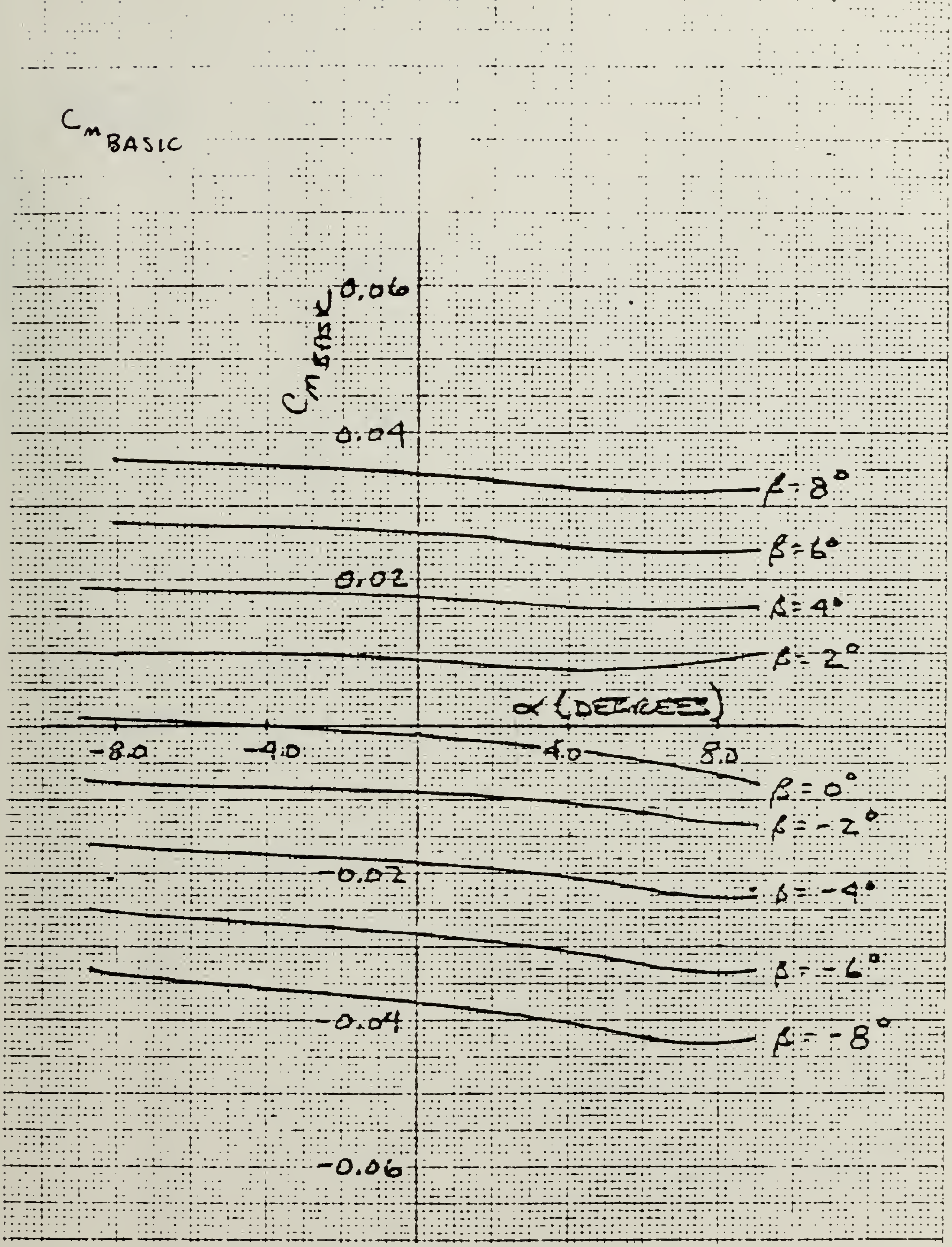
α vs β vs $C_{y_{basic}}$

$C_{\ell_{BASIC}}$



Side Slip Characteristic

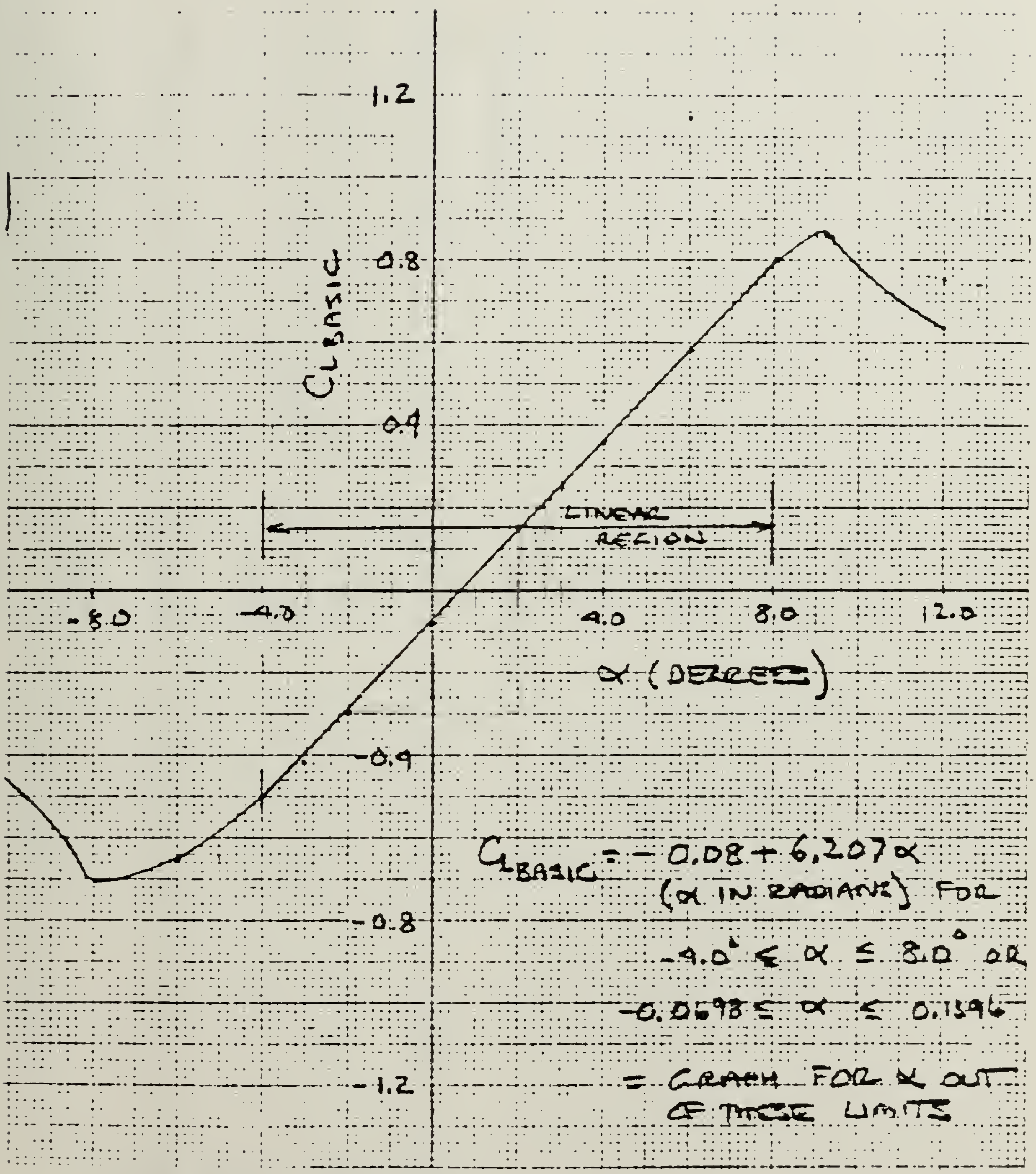
α vs β vs $C_{l_{basic}}$



Side Slip Characteristics

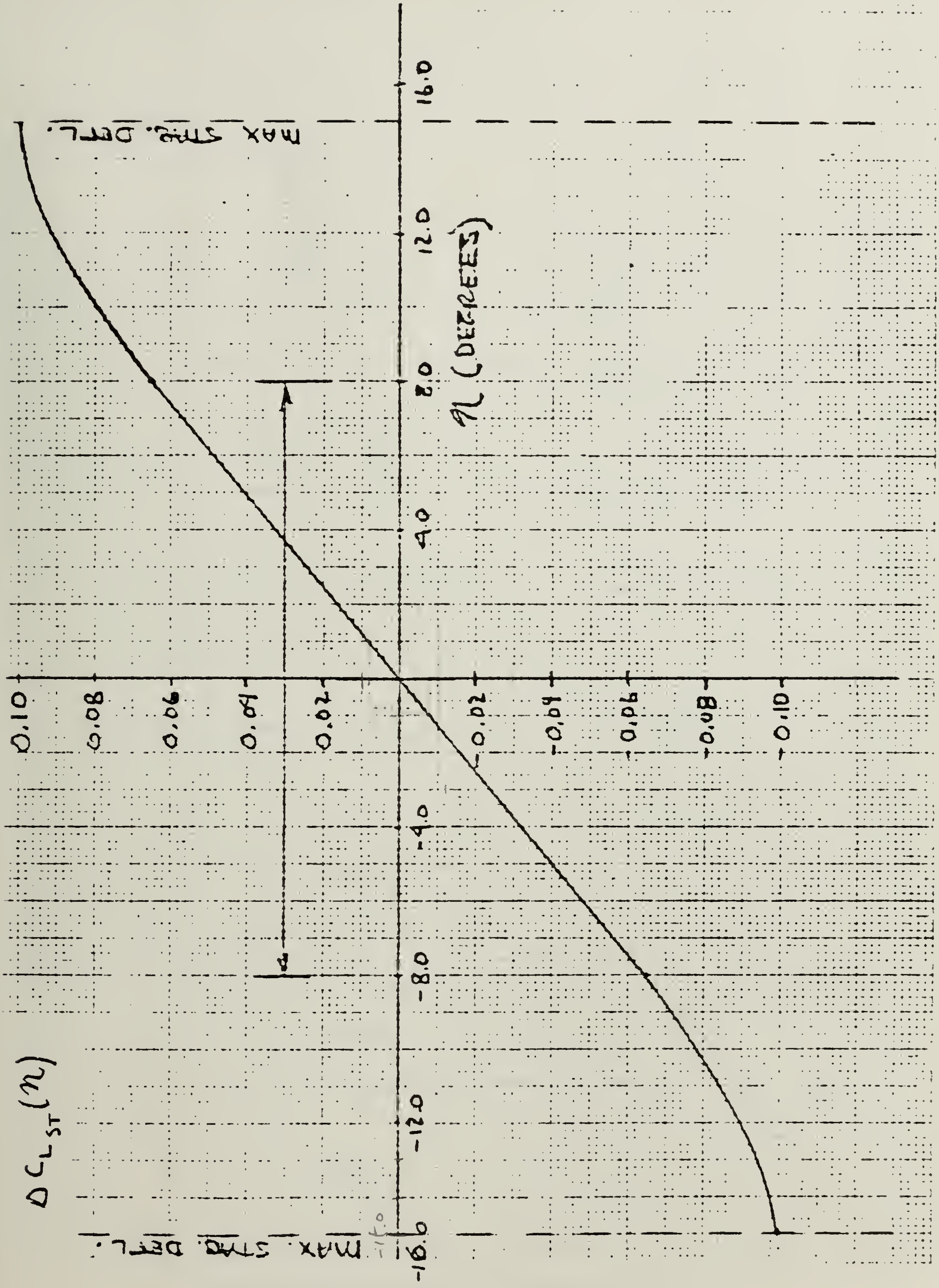
α vs β vs $C_{n_{basic}}$

$C_{L_{BASIC}}$



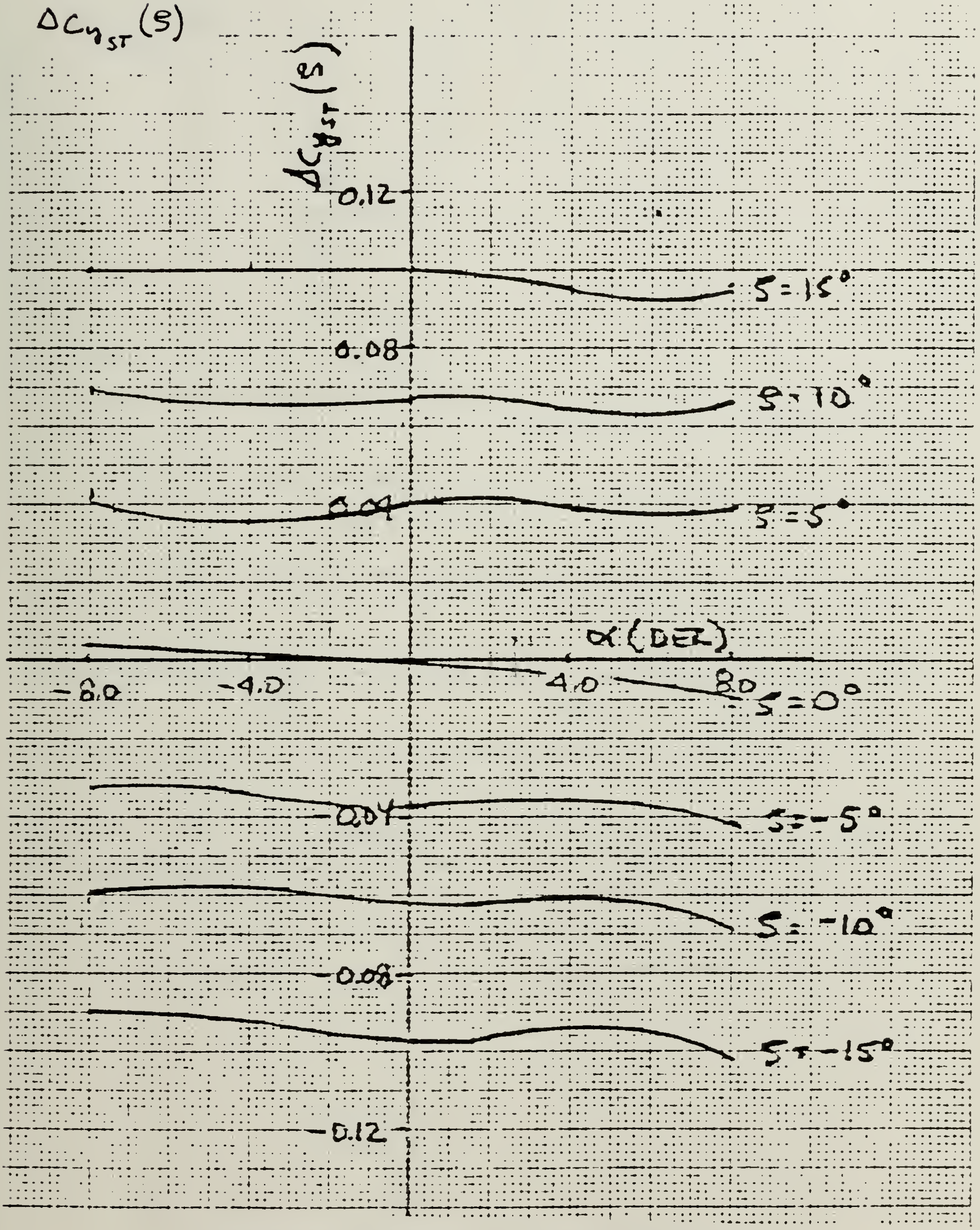
Lift Characteristics

α vs $C_{L_{basic}}$



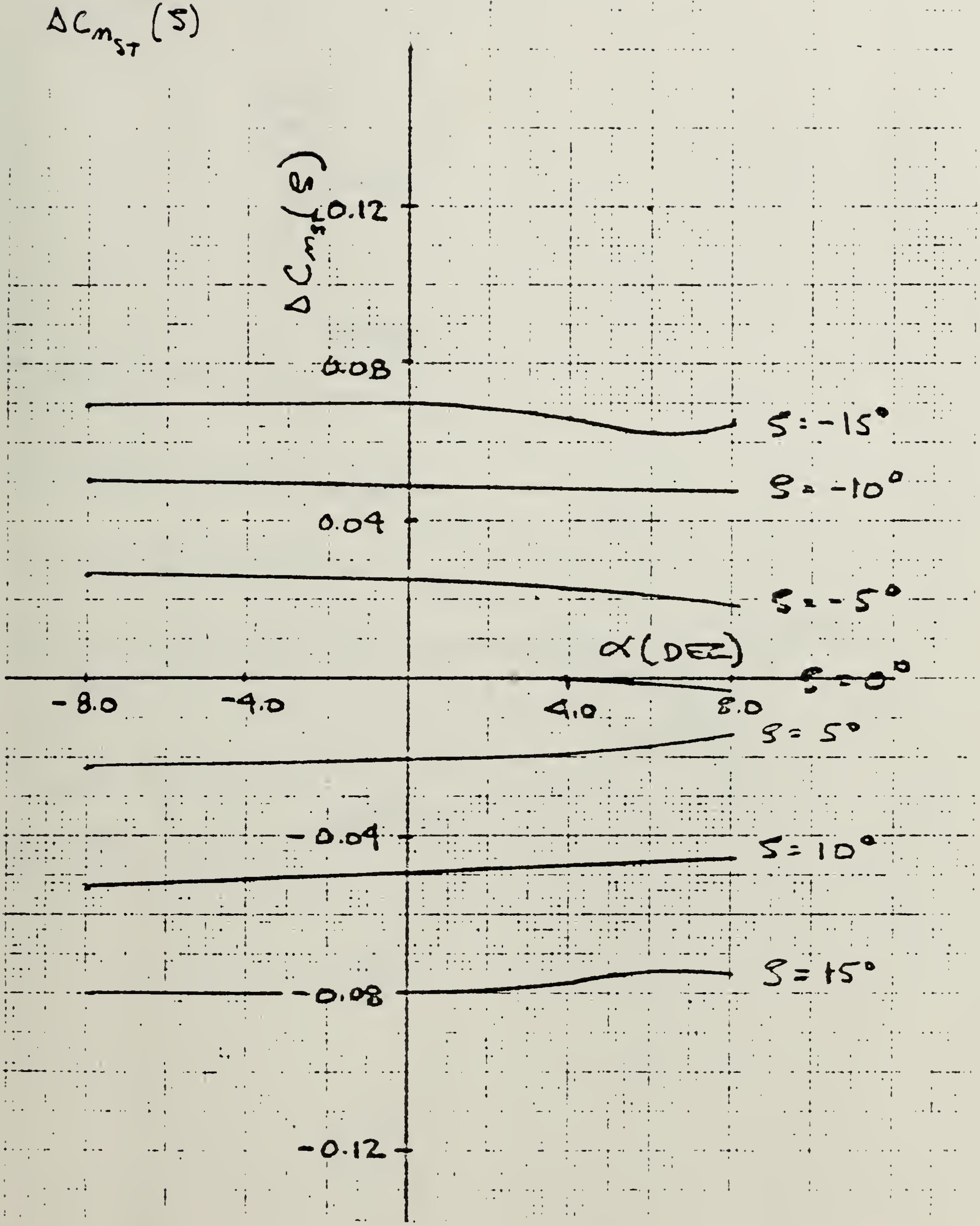
Lift Characteristics

η vs $\Delta C_{L_{ST}}(\eta)$



Directional Control Characteristics

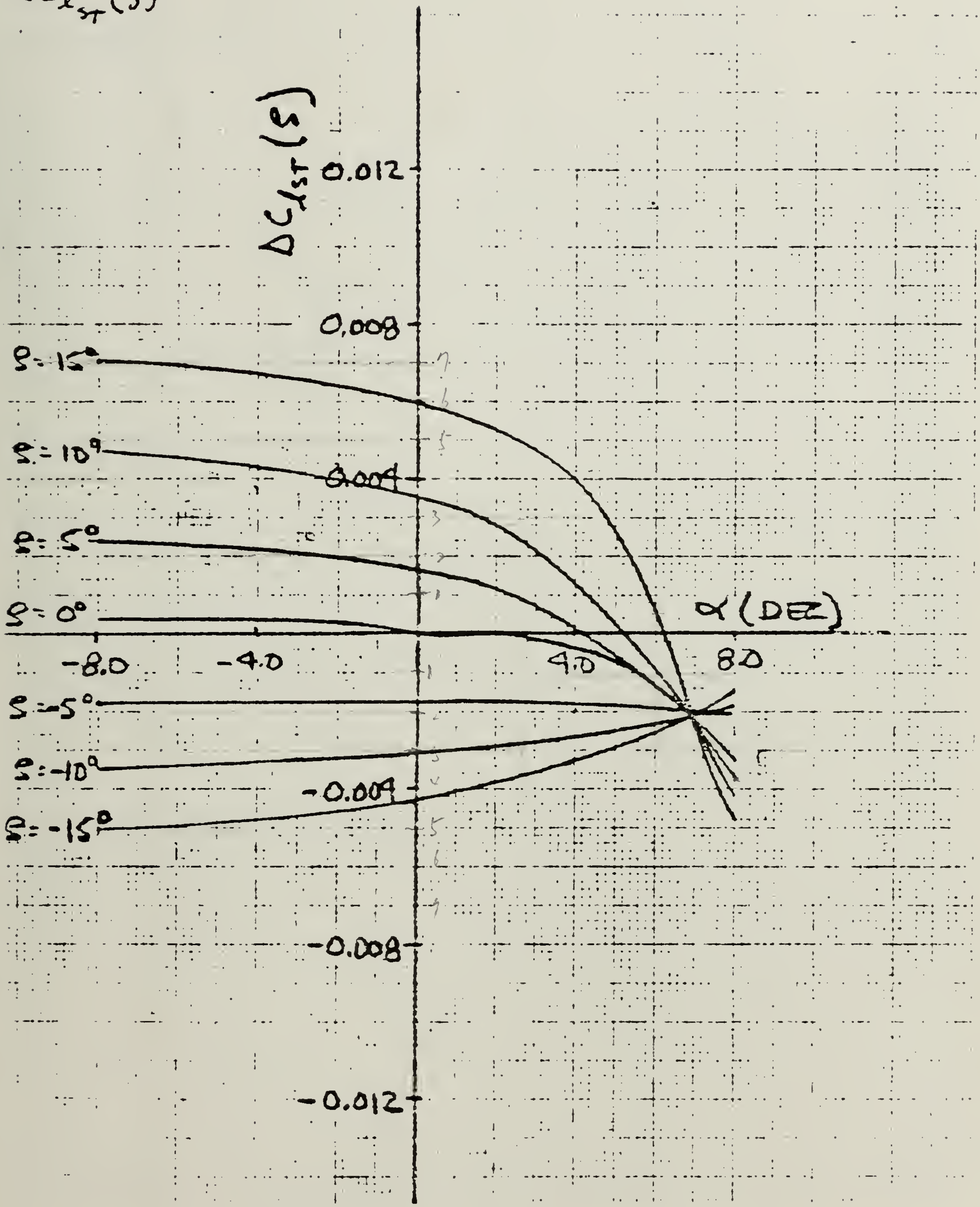
α vs ζ vs $\Delta C_{Y_{ST}}$ (ζ)



Directional Control Characteristics

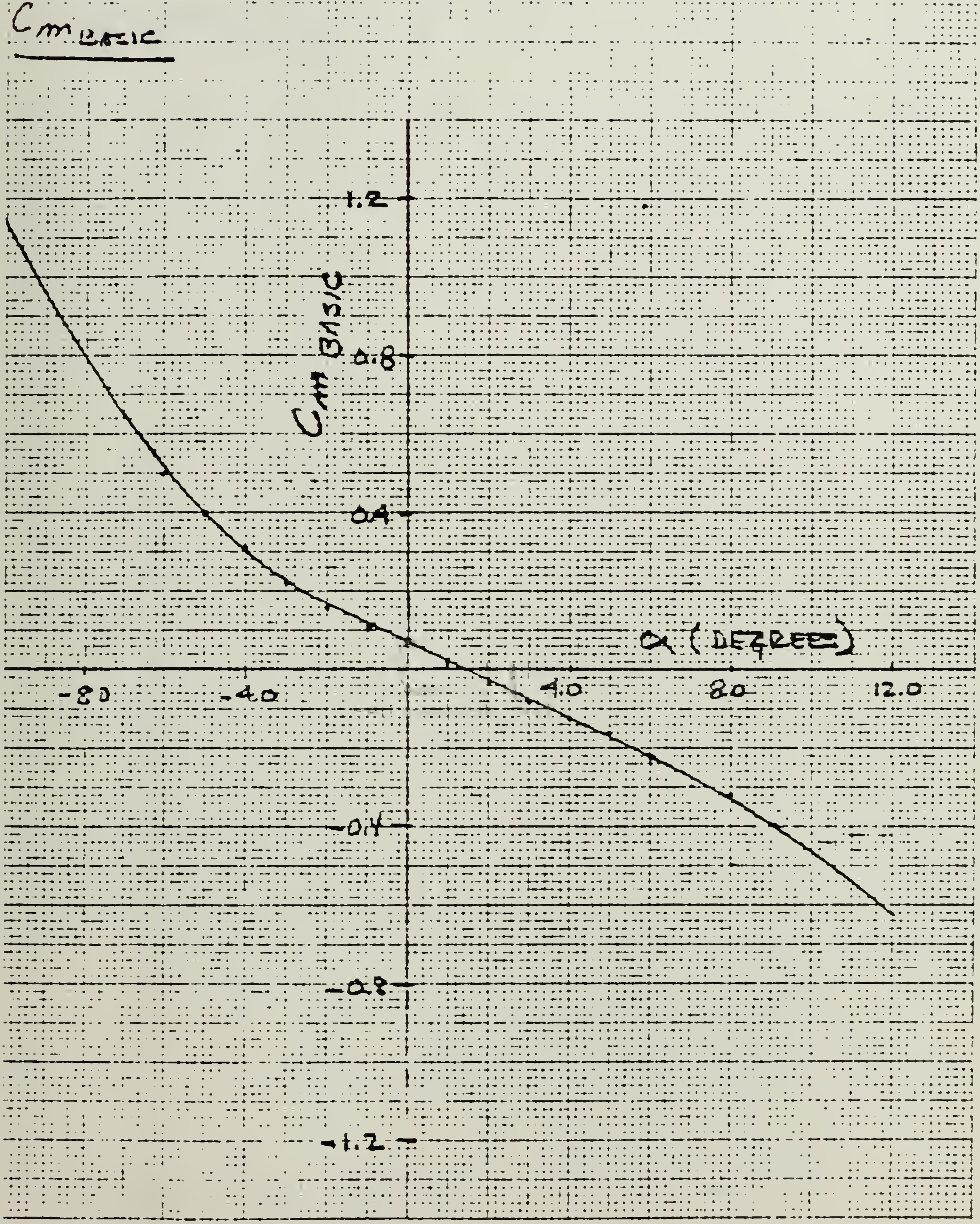
α vs ζ vs $\Delta C_{n_{ST}}(\zeta)$

$\Delta C_{l_{ST}}(\zeta)$



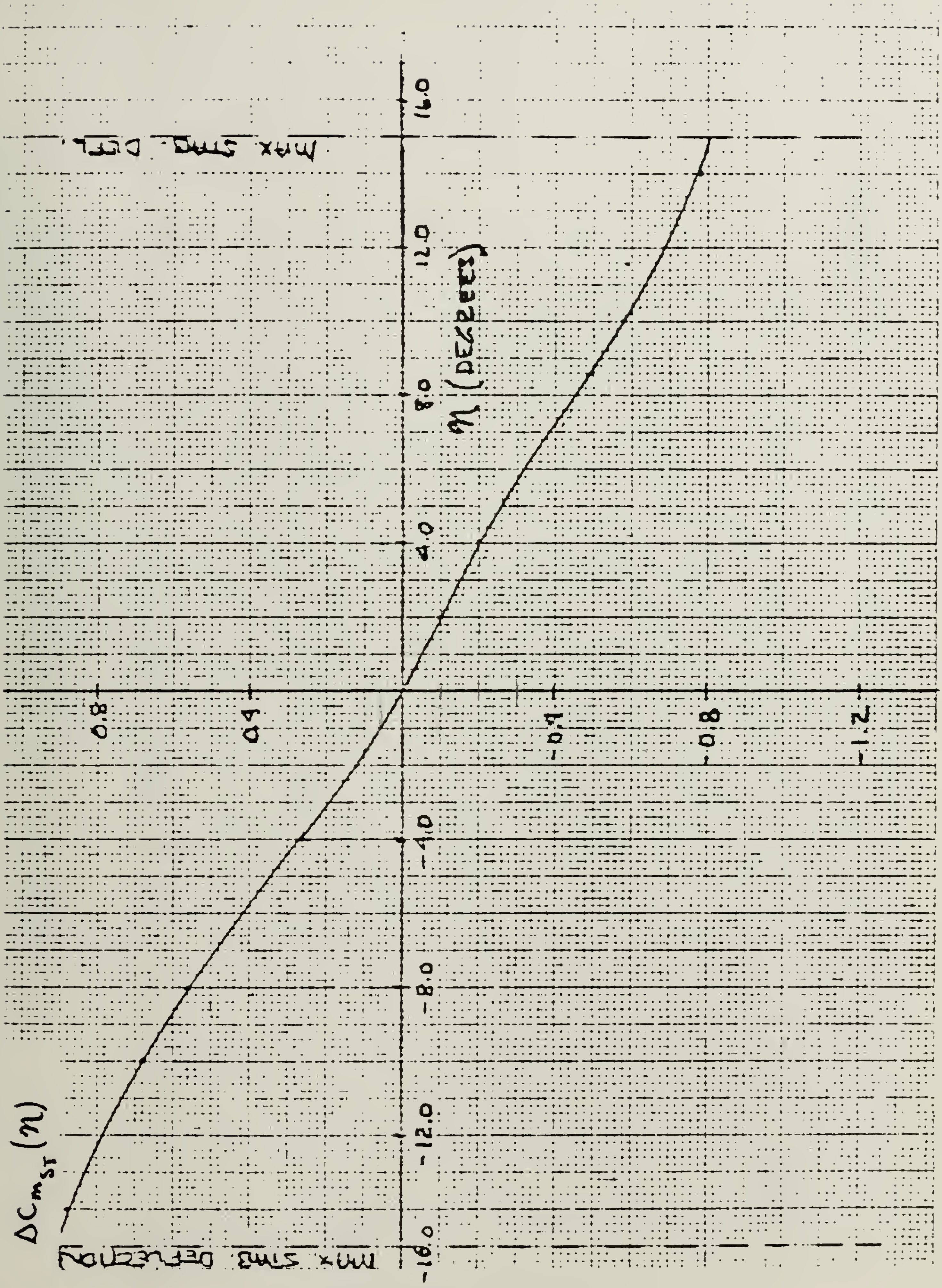
Directional Control Characteristics

α vs ζ vs $\Delta C_{l_{ST}}(\zeta)$



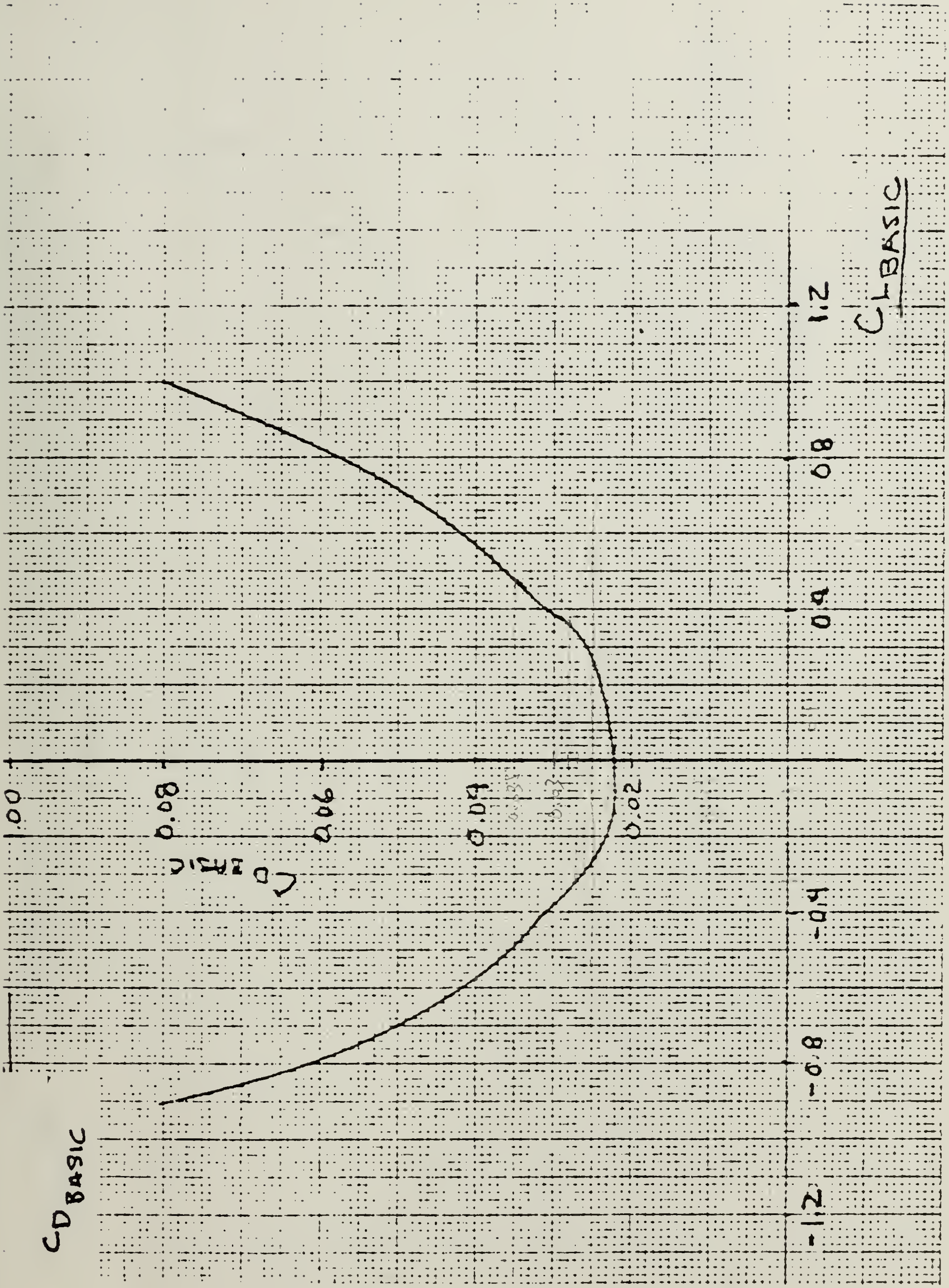
Pitching Moment Characteristics

α vs $C_{M_{basic}}$



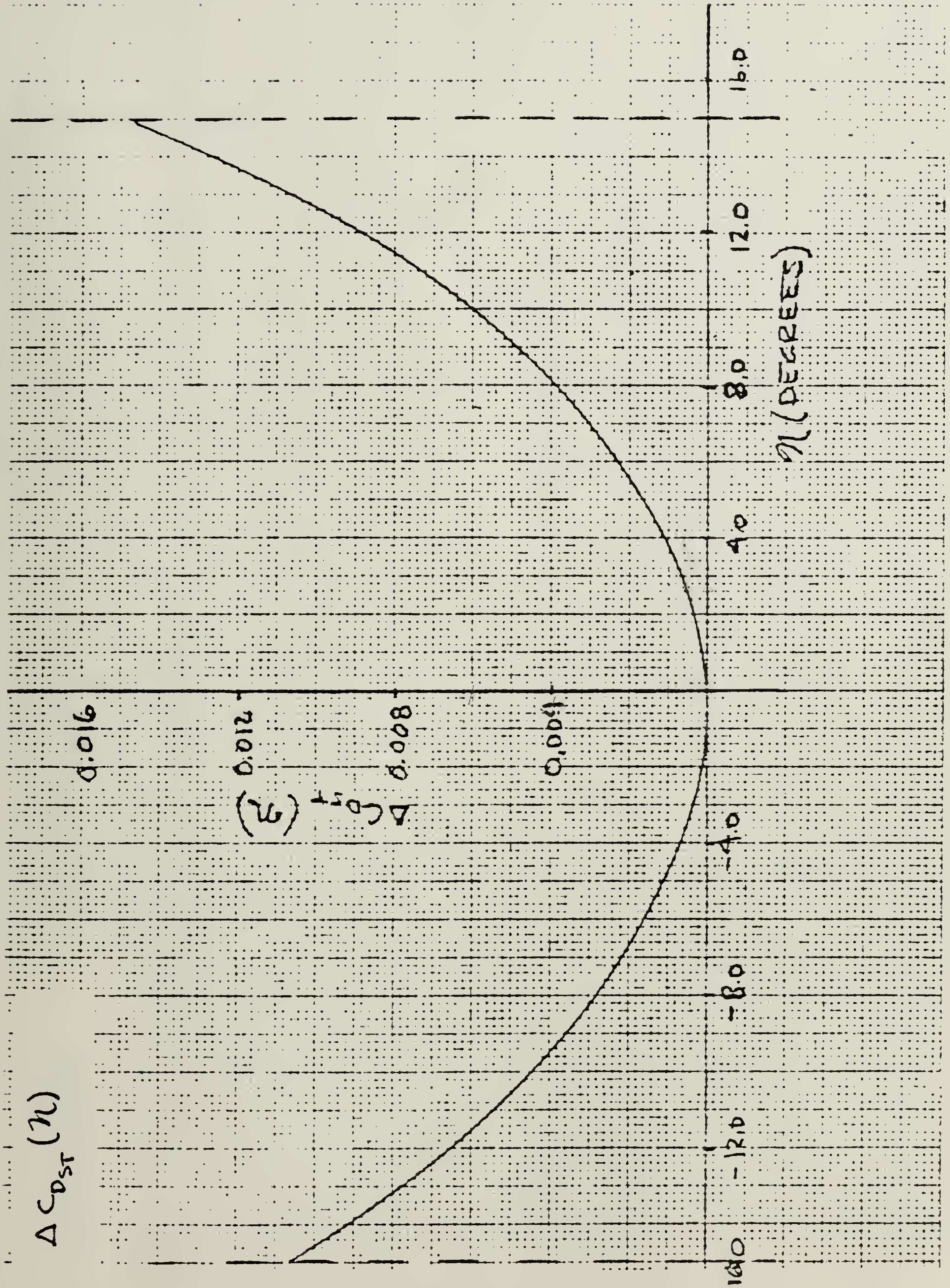
Pitching Moment Characteristics

η vs $\Delta C_{m_{ST}}(\eta)$



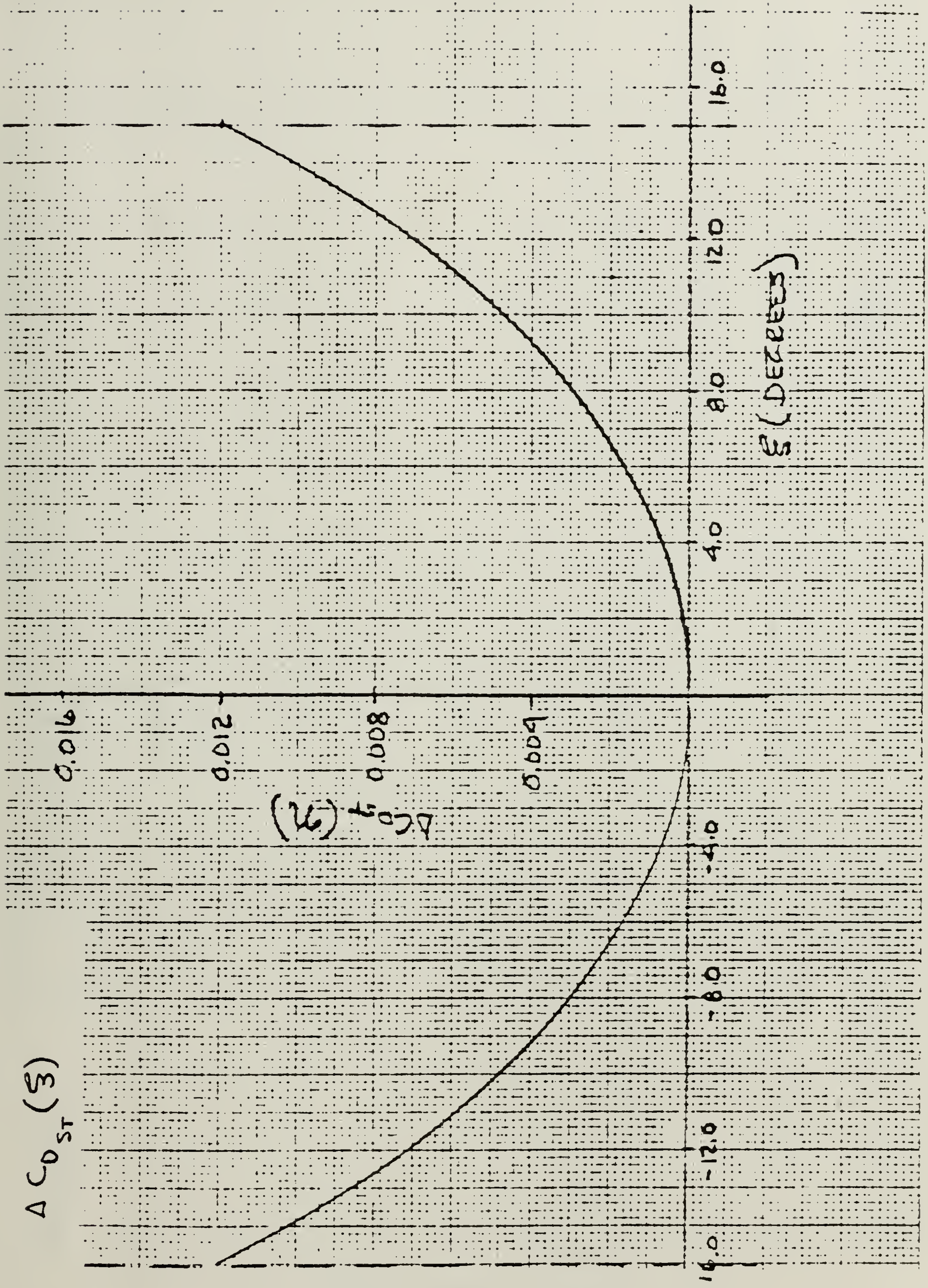
Drag Characteristics

$C_{L_{basic}}$ vs $C_{D_{basic}}$



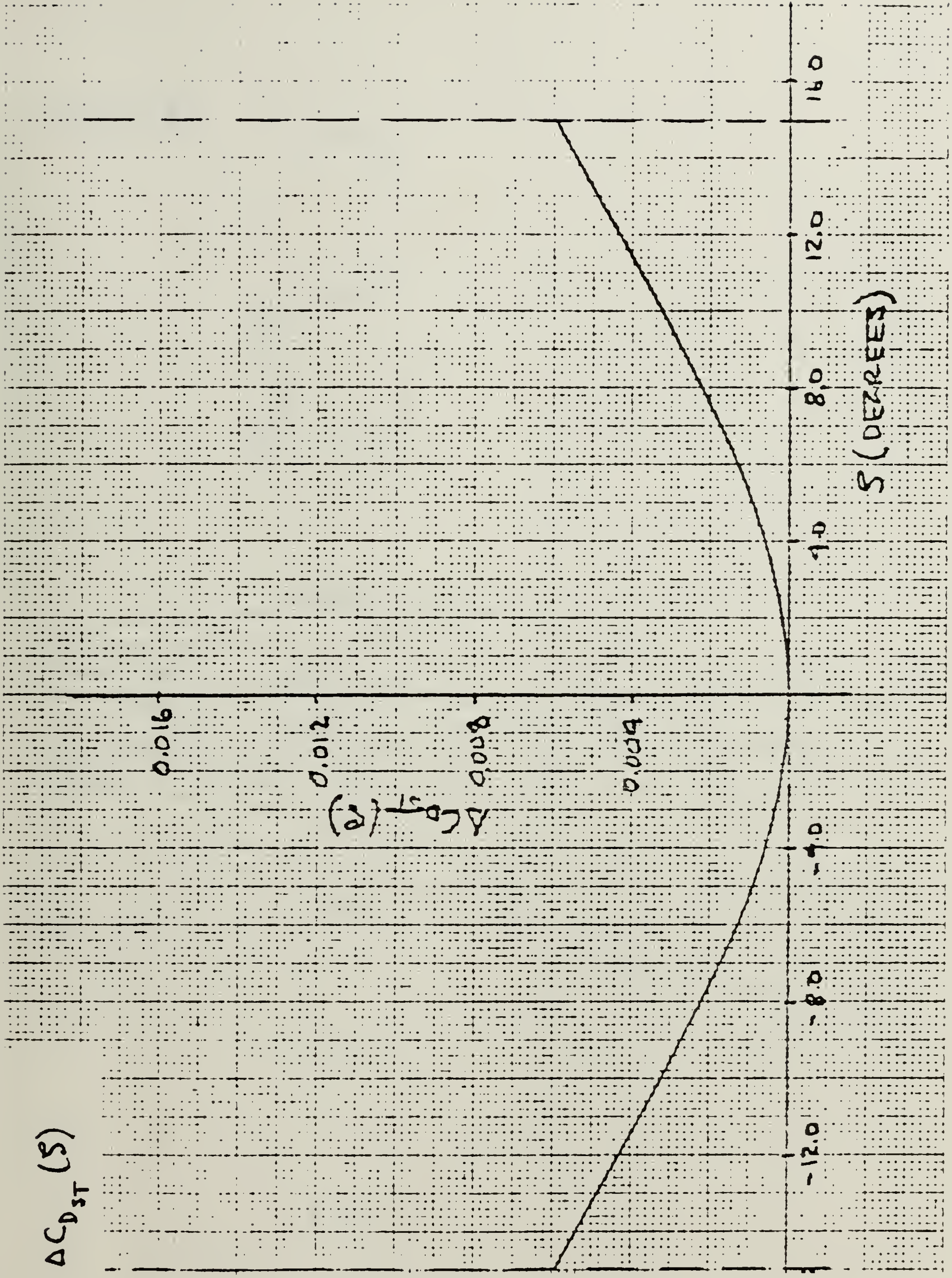
Drag Characteristics

η vs $\Delta C_{D_{ST}}(\eta)$



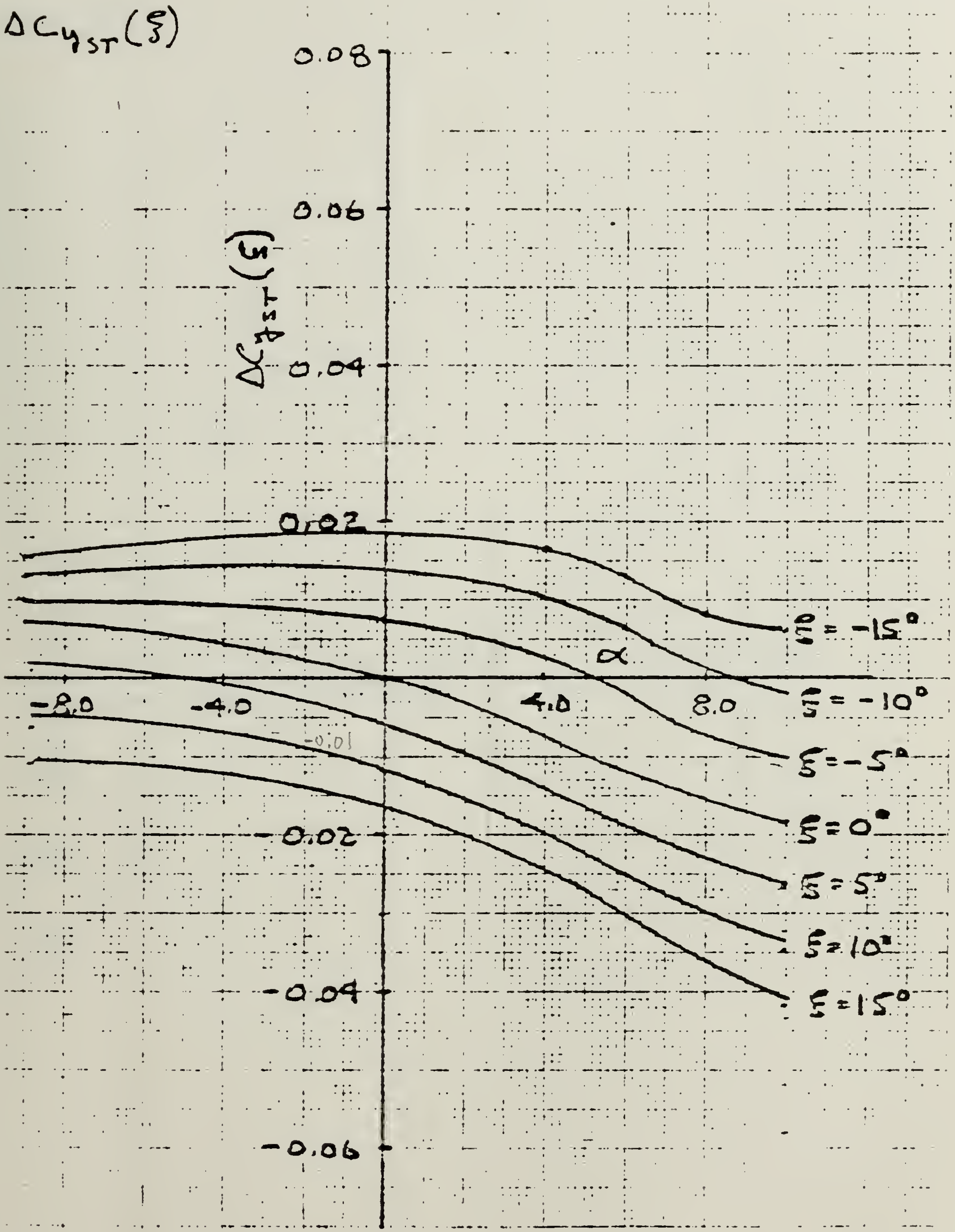
Drag Characteristics

ξ vs $\Delta C_{D_{ST}}$ (ξ)



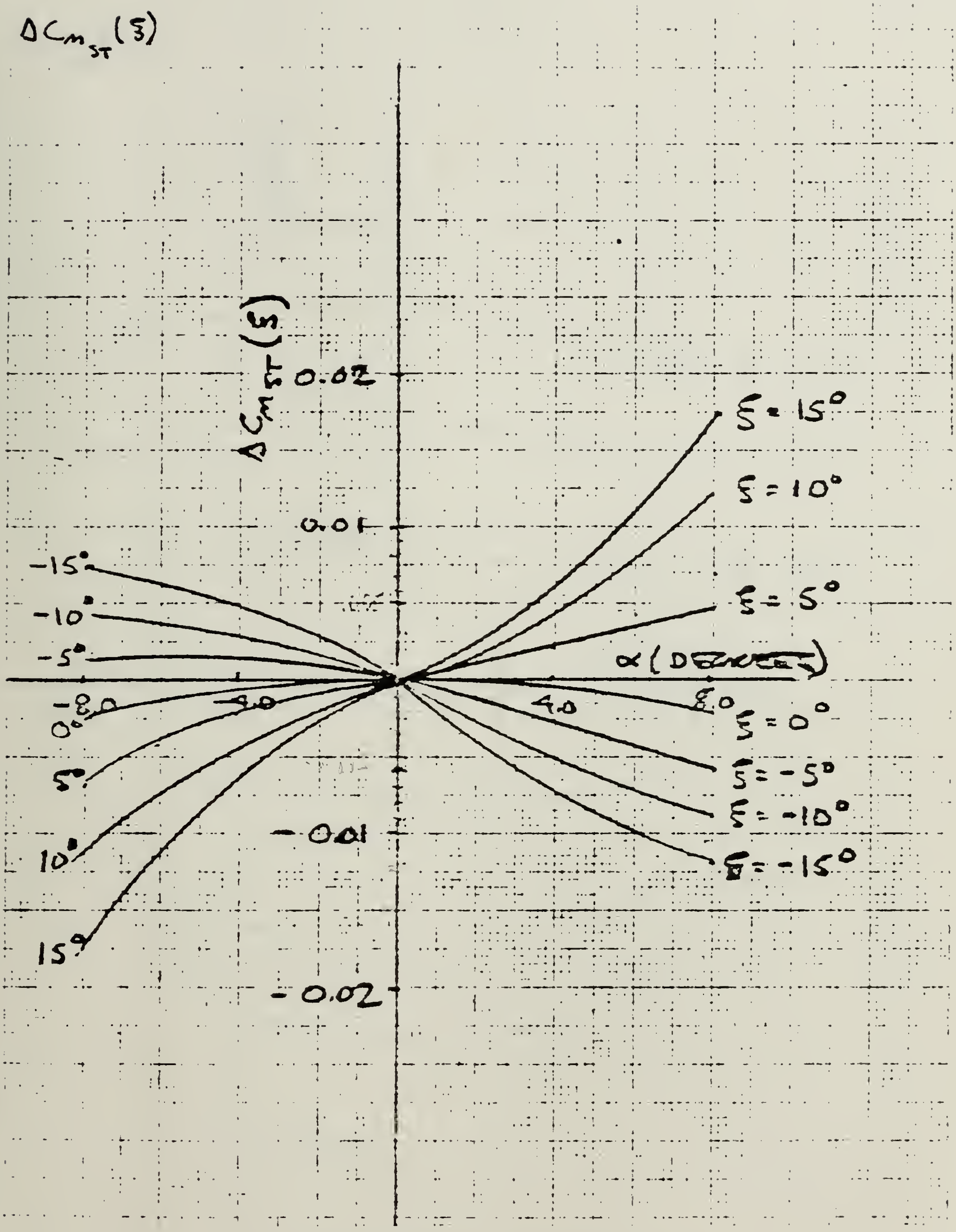
Drag Characteristics

ζ vs $\Delta C_{D_{ST}}(\zeta)$



Lateral Control Characteristics

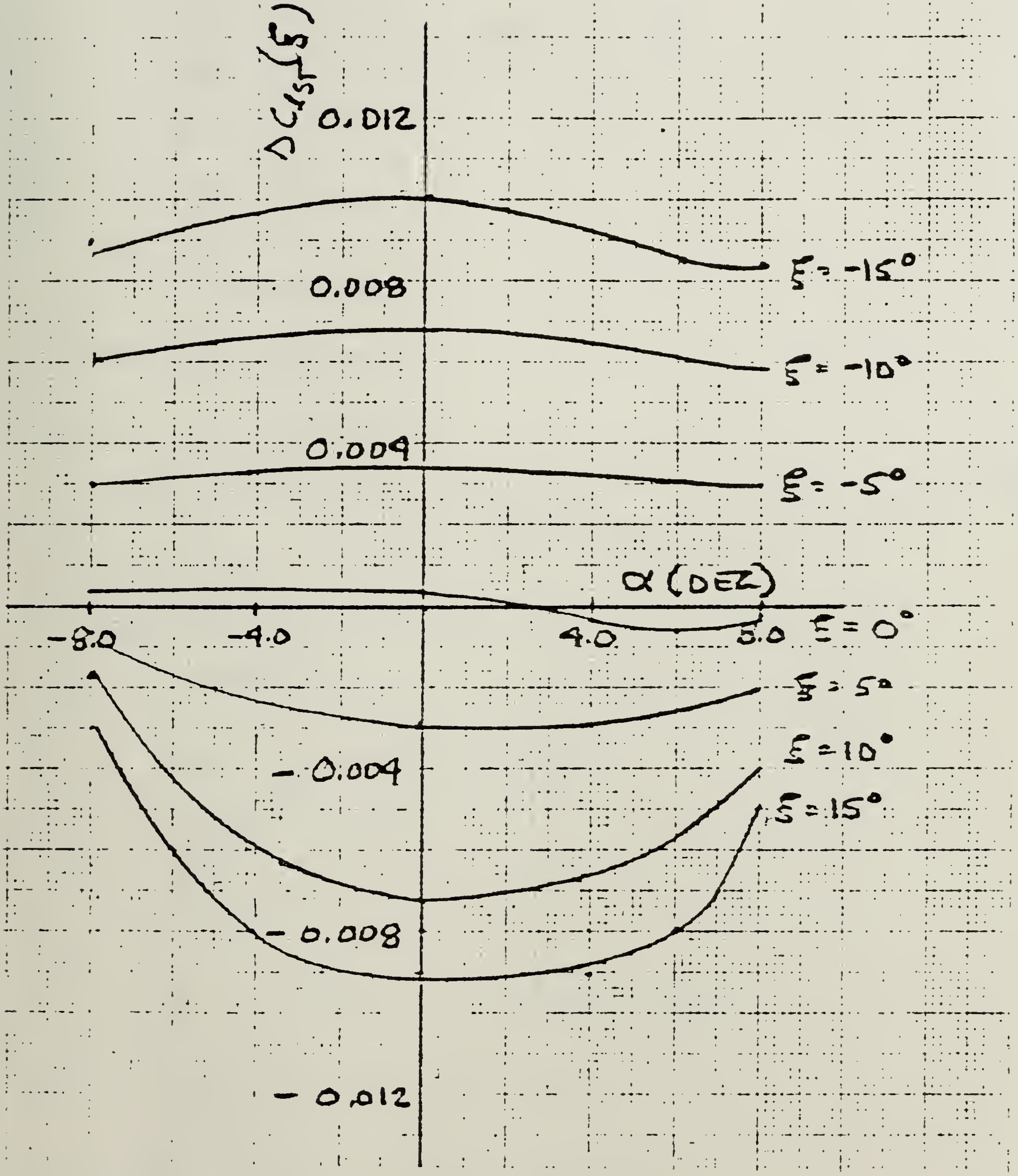
α vs ξ vs $\Delta C_{y_{ST}}(\xi)$



Lateral Control Characteristics

α vs ξ vs $\Delta C_{n_{ST}}(\xi)$

$\Delta C_{l_{ST}}(\xi)$



Lateral Control Characteristics

α vs ξ vs $\Delta C_{l_{ST}}(\xi)$

APPENDIX B

STEADY STATE DATA

W = 2200 LBS (At end of cruise flight) = 2200 × 0.454 kg = 998.8

m = 68.38 Slugs = 68.38 × 14.6188 kg = 999.6 kg

S = 12 feet^2

$\bar{b}$ = 8.485 Feet

$\bar{c}$ = 1.414 Feet

I_{xx} = 27.8 Slug feet^2

I_{yy} = 1507 Slug feet^2

I_{zz} = 1512 Slug feet^2

I_{xz} = 11.7 Slug feet^2

$T_x = T$ = 600 LBS = 600 lbf = 600 × 0.454 kg × 9.81 m/s^2 = 26[illegible] N

M = 0.75

$V_{T_{SS}}$ = 839 Feet/Sec

$$\bar{q}_{SS} = \tfrac{1}{2}\,\rho_{SL} V_{T_{SS}} = 837 \text{ LBS/feet}^2$$

$$C_{L_{SS}} = \frac{W}{q_{SS} S} = 0.219$$

$C_{D_{SS}}$ = 0.0242

$\alpha_{SS} = \theta_{SS}$ = 2.65° = 0.04625 Radian

$$T_{SS} = \frac{C_{D_{SS}}\,\bar{q}_{SS} S}{\cos\alpha_{SS}} = 243.3 \text{ LBS}$$

$$W_{SS} = V_{T_{SS}} \sin\alpha_{SS} = 38.79 \text{ Feet/sec}$$

$U_{SS} = V_{T_{SS}} \cos \alpha_{SS} = 838.1$ Feet/sec

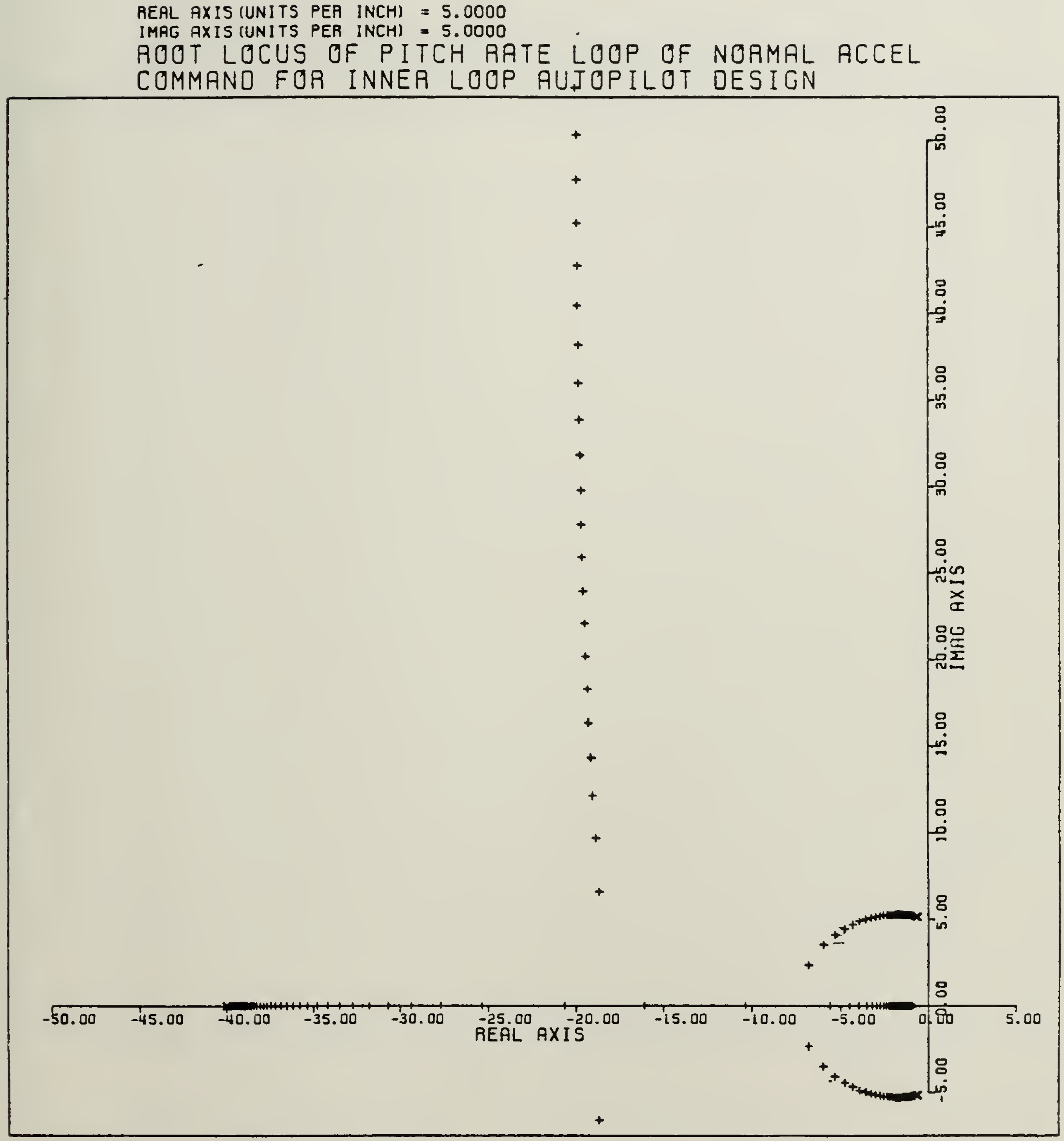
$C_{m_{basic_{SS}}} = -0.06$

$C_{m_{ST_{SS}}} = 0$

$\eta_{SS} = -1.0^{\circ} = 0.01745$ Radian

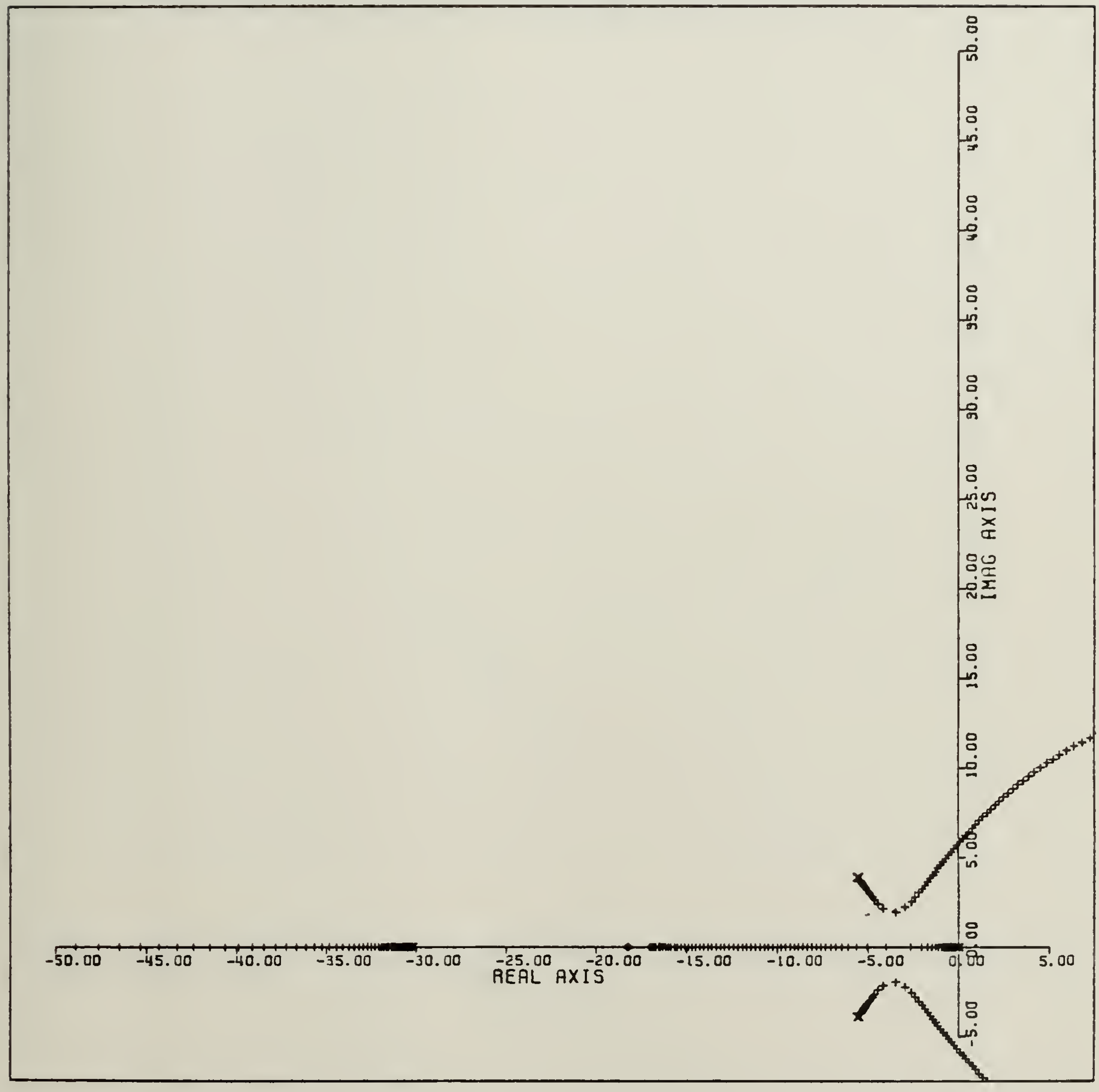
APPENDIX C

AUTOPILOT ROOT LOCUS PLOTS



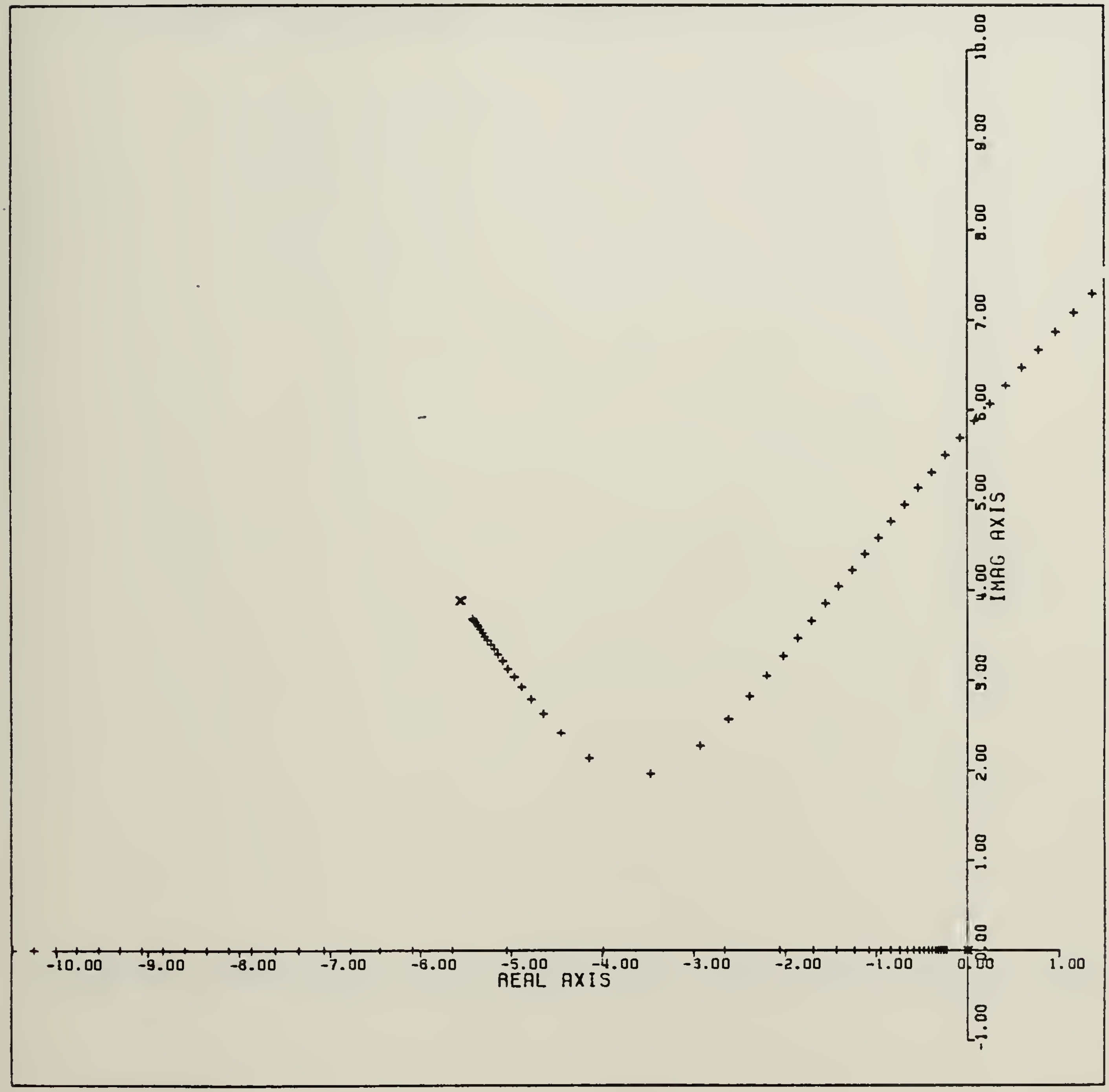
REAL AXIS (UNITS PER INCH) = 5.0000
IMAG AXIS (UNITS PER INCH) = 5.0000

ROOT LOCUS OF NORMAL ACCELERATION COMMAND
FOR INNER LOOP AUTOPILOT DESIGN



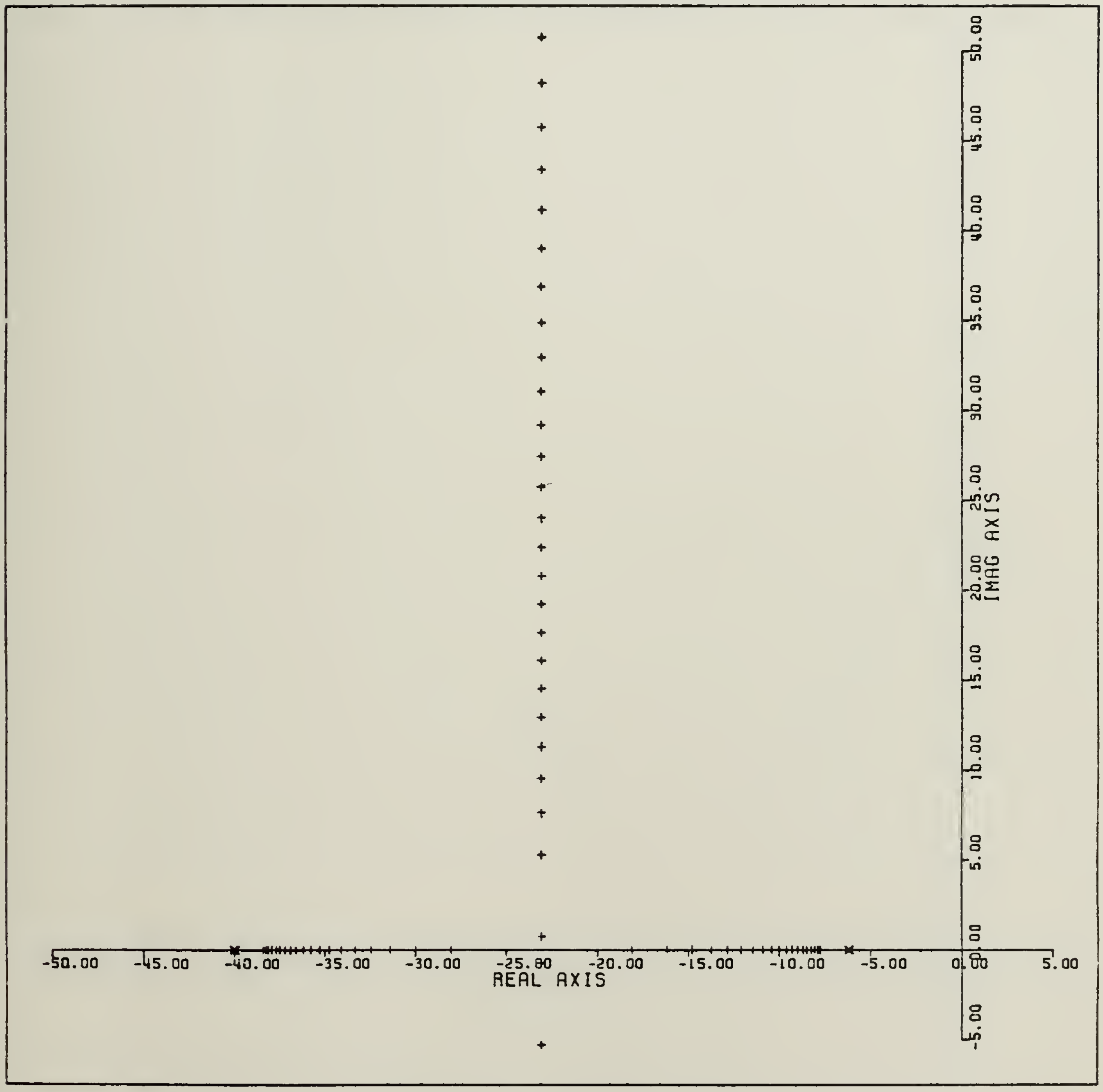
REAL AXIS (UNITS PER INCH) = 1.0000
IMAG AXIS (UNITS PER INCH) = 1.0000

ROOT LOCUS OF NORMAL ACCELERATION
COMMAND FOR INNER LOOP AUTOPILOT DESIGN



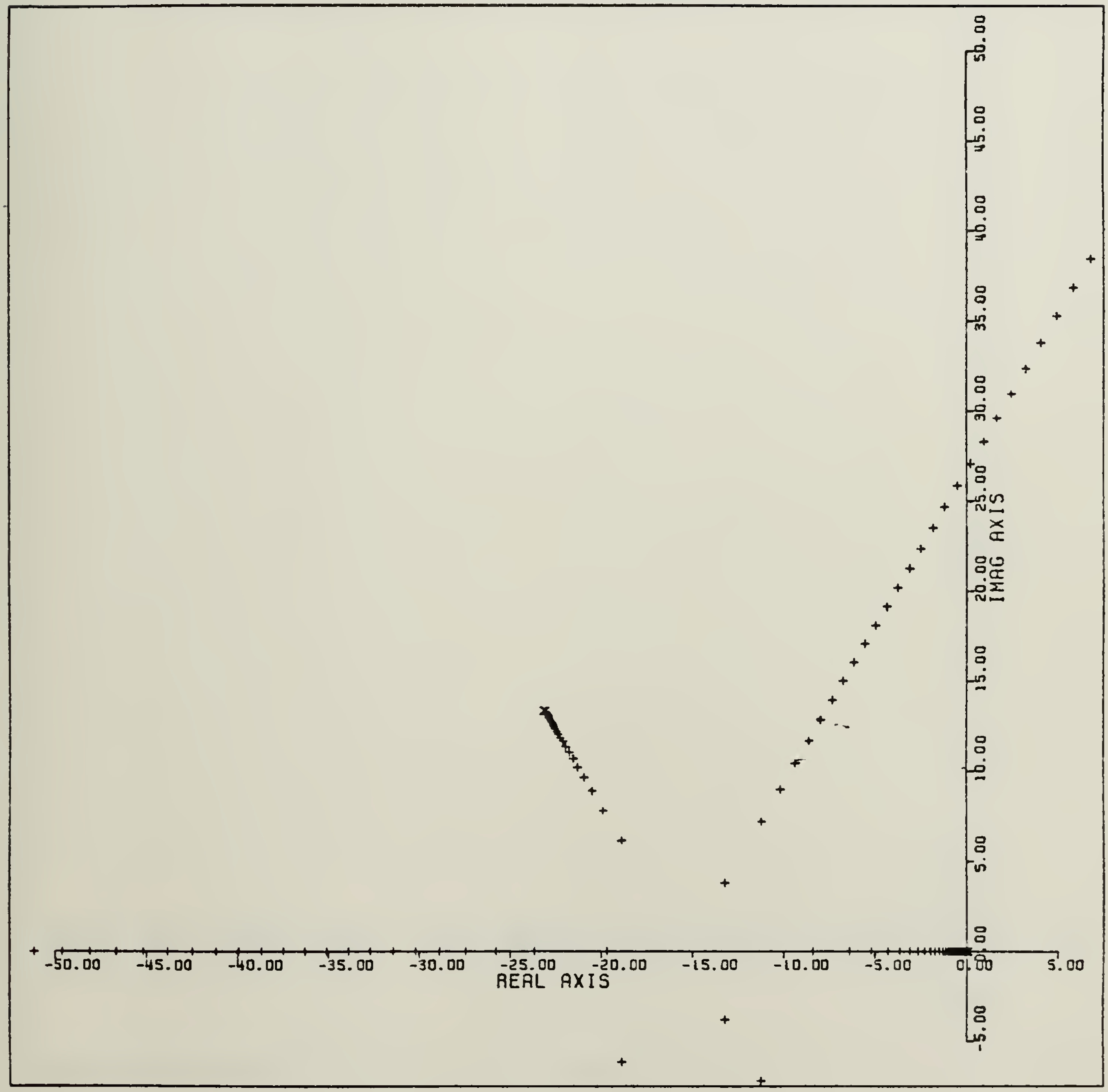
REAL AXIS (UNITS PER INCH) = 5.0000
IMAG AXIS (UNITS PER INCH) = 5.0000

ROOT LOCUS OF ROLL RATE LOOP OF BANK ANGLE COMMAND FOR INNER LOOF AUTOPILOT DESIGN



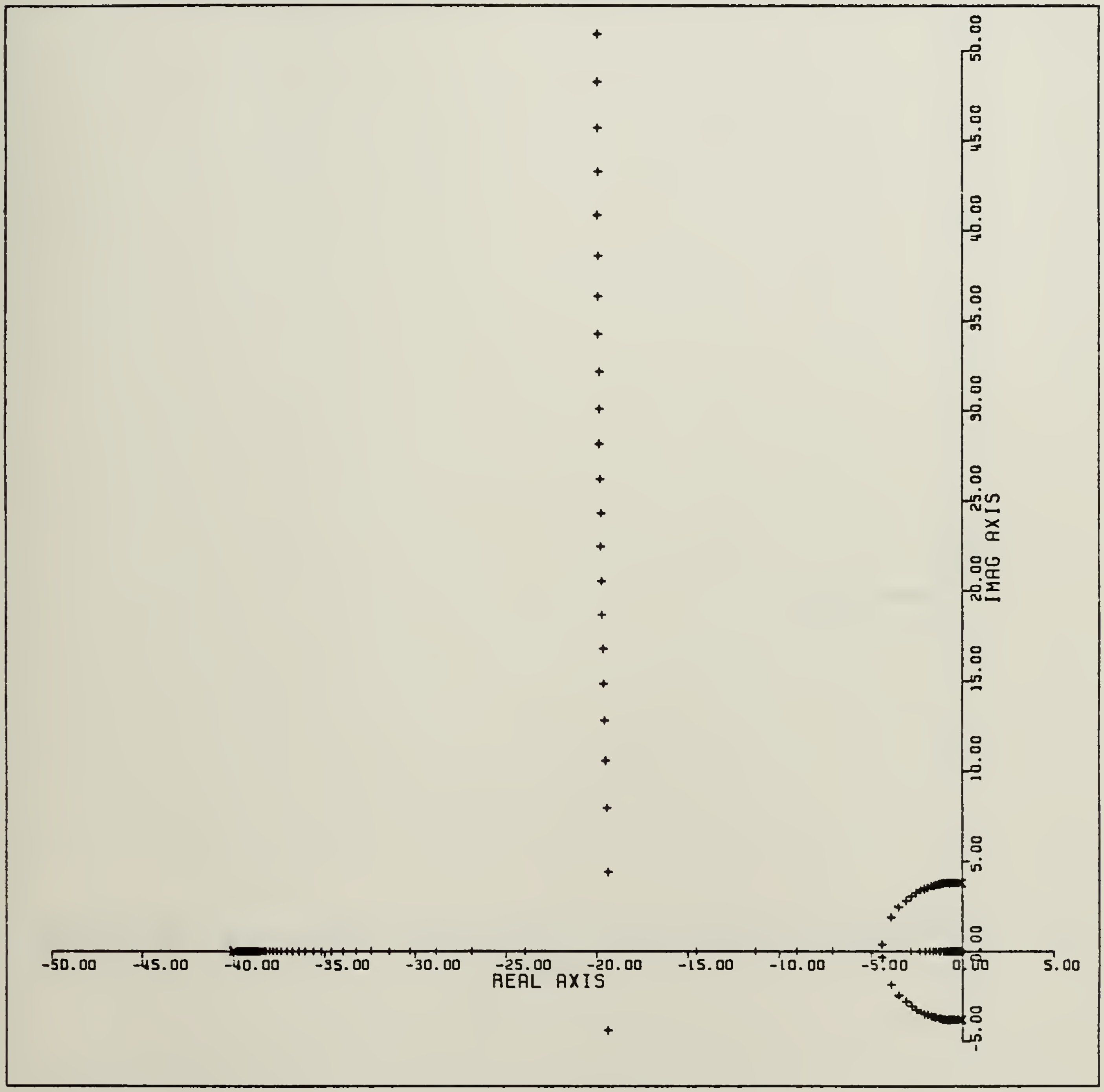
REAL AXIS (UNITS PER INCH) = 5.0000
IMAG AXIS (UNITS PER INCH) = 5.0000

ROOT LOCUS OF BANK ANGLECOMMAND
FOR INNER LOOP AUTOPILOT DESIGN



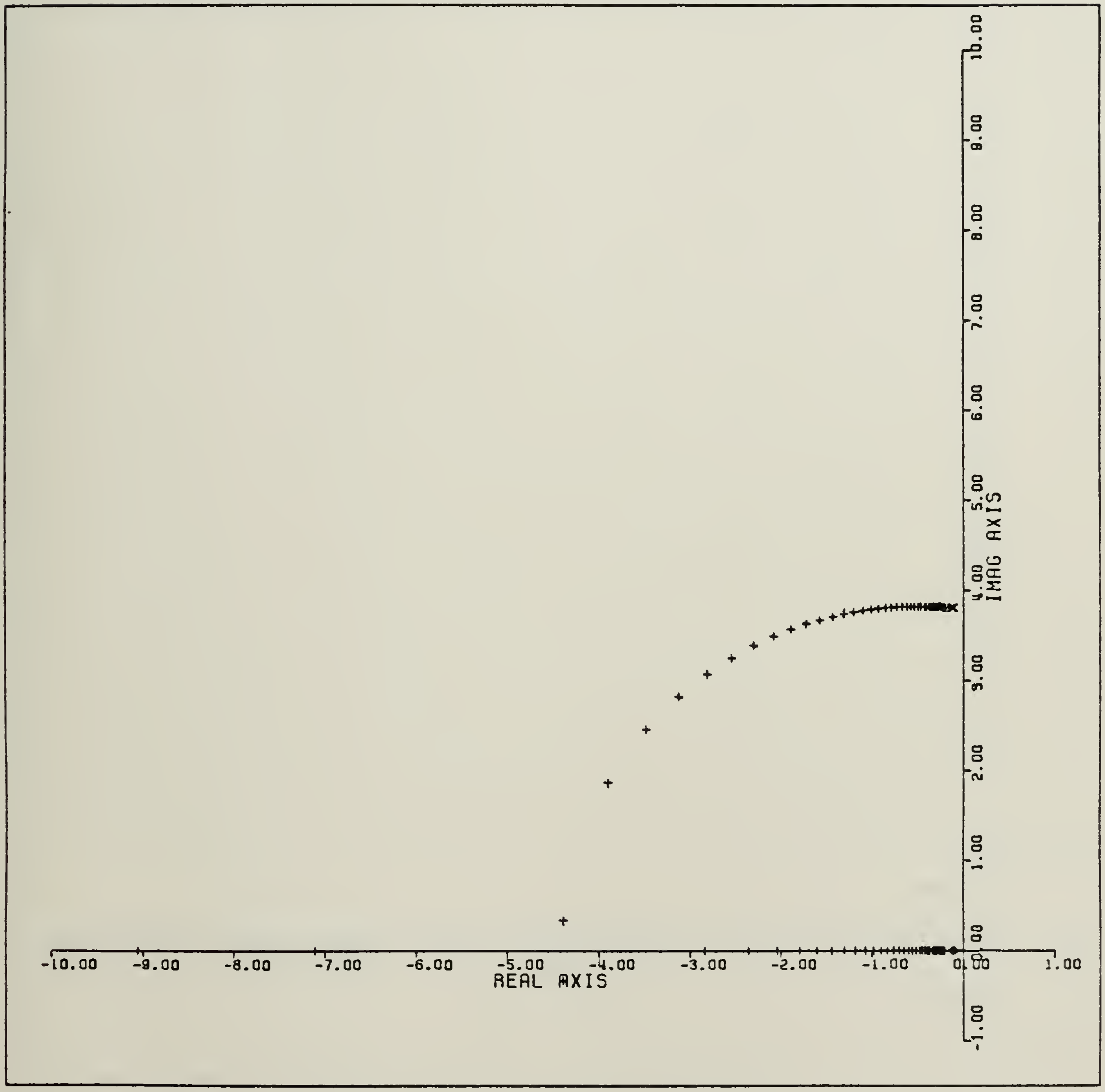
REAL AXIS (UNITS PER INCH) = 5.0000
IMAG AXIS (UNITS PER INCH) = 5.0000

ROOT LOCUS OF YAW RATE LOOP OF TURN COORDINATOR FOR INNER LOOP AUTOPILOT DESIGN

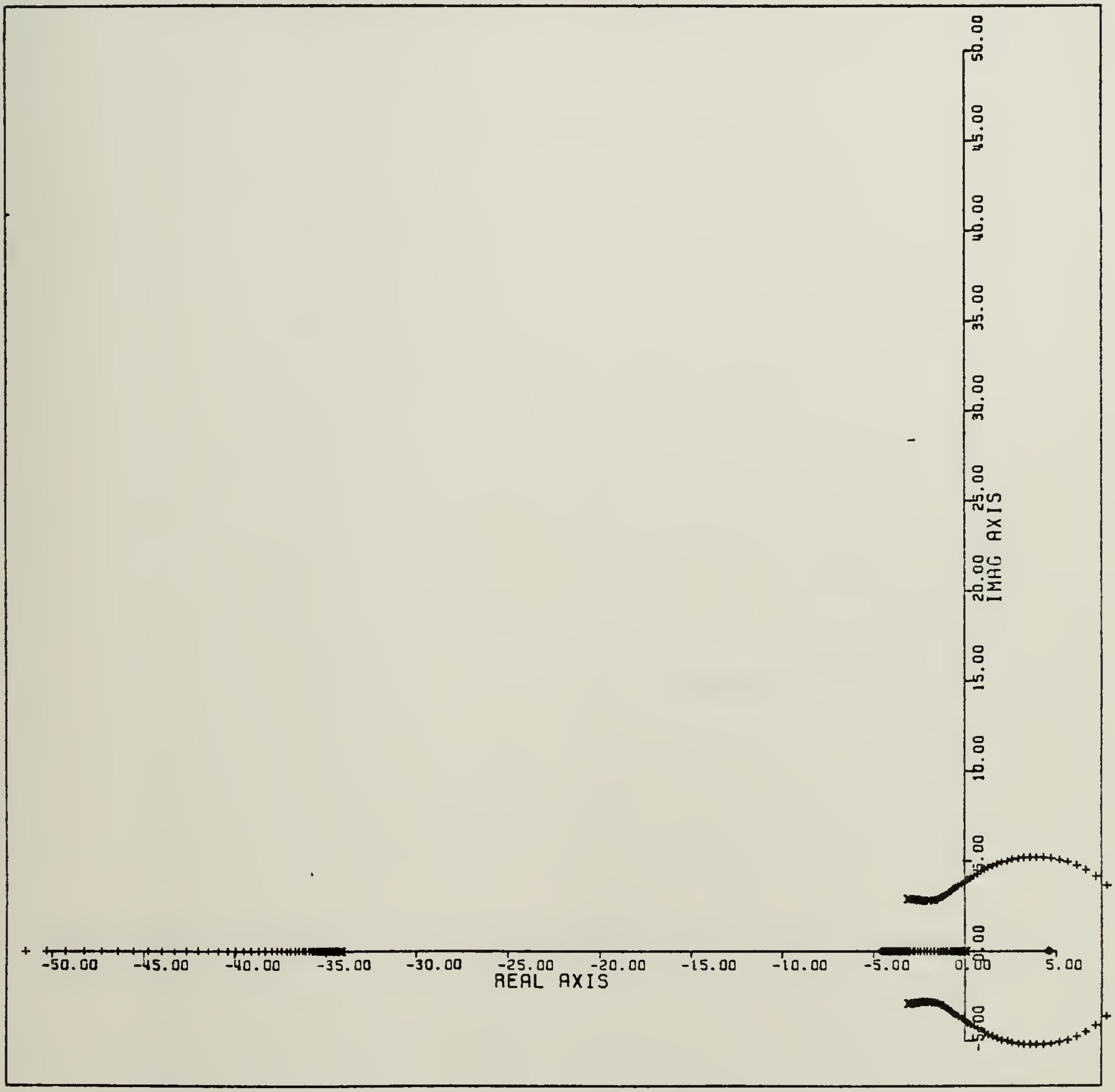


REAL AXIS (UNITS PER INCH) = 1.0000
IMAG AXIS (UNITS PER INCH) = 1.0000

ROOT LOCUS OF YAW RATE LOOP OF TURN COORDINATOR FOR INNER LOOP AUTOPILOT DESIGN

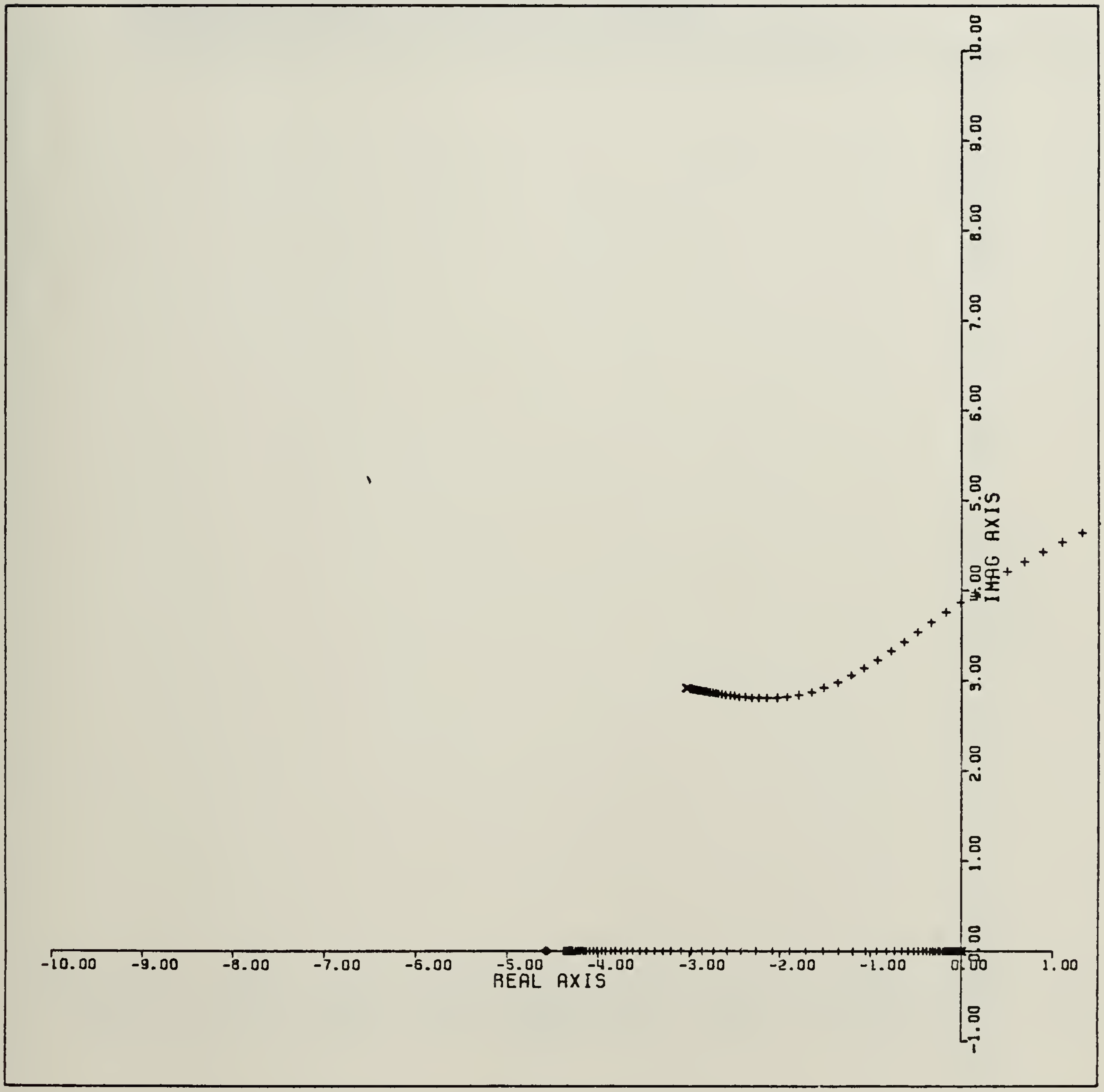


REAL AXIS (UNITS PER INCH) = 5.0000
IMAG AXIS (UNITS PER INCH) = 5.0000
ROOT LOCUS OF TURN COORDINATOR
FOR INNER LOOP AUTOPILOT DESIGN



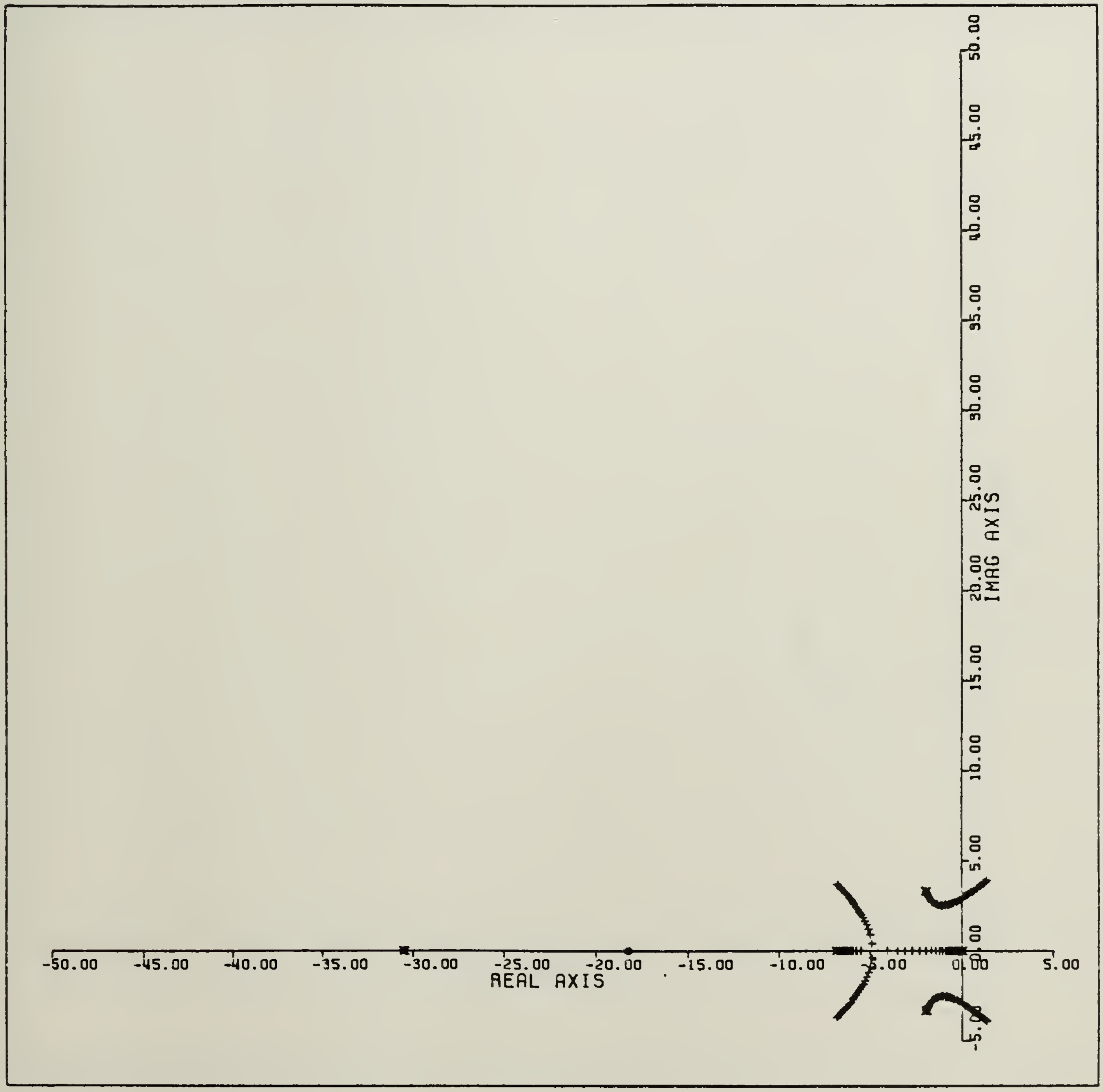
REAL AXIS (UNITS PER INCH) = 1.0000
IMAG AXIS (UNITS PER INCH) = 1.0000

ROOT LOCUS OF TURN COORDINATOR
FOR INNER LOOP AUTOPILOT DESIGN



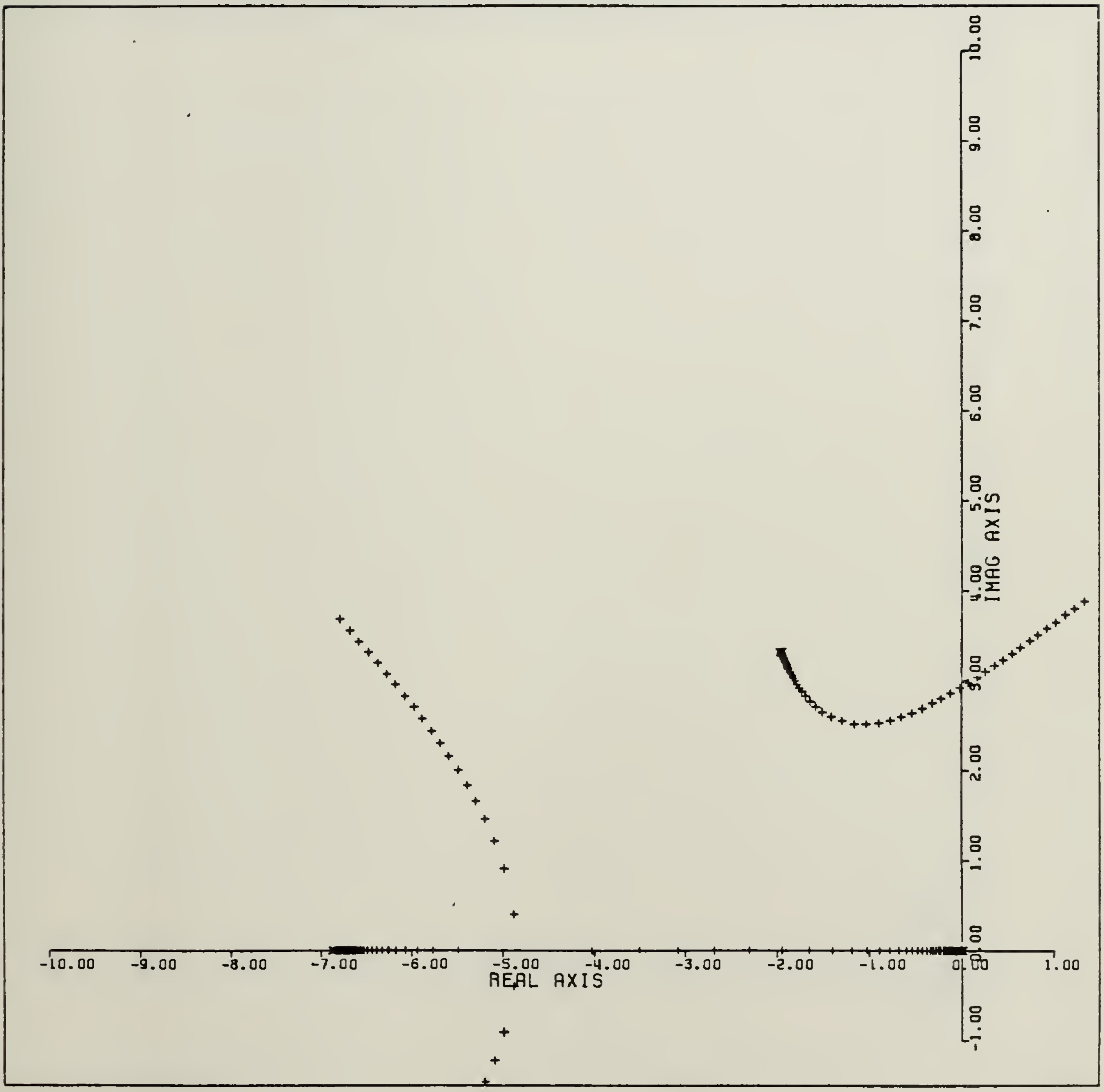
REAL AXIS (UNITS PER INCH) = 5.0000
IMAG AXIS (UNITS PER INCH) = 5.0000

ROOT LOCUS OF FLIGHT PATH ANGLE COMMAND FOR OUTER LOOP AUTOPILOT DESIGN



REAL AXIS (UNITS PER INCH) = 1.0000
IMAG AXIS (UNITS PER INCH) = 1.0000

ROOT LOCUS OF FLIGHT PATH ANGLE
COMMAND FOR OUTER LOOP AUTOPILOT DESIGN



REAL AXIS (UNITS PER INCH) = 5.0000
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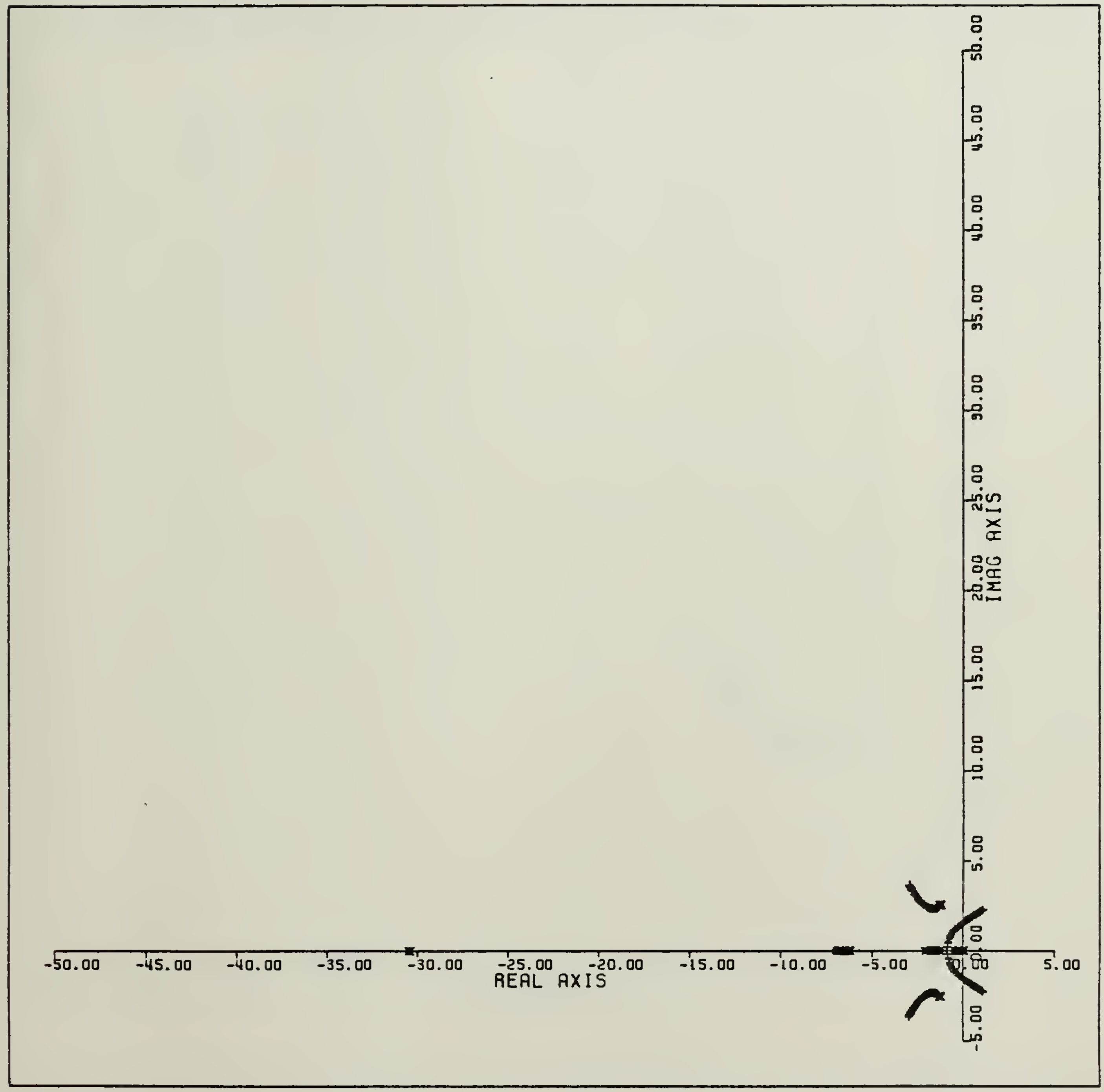
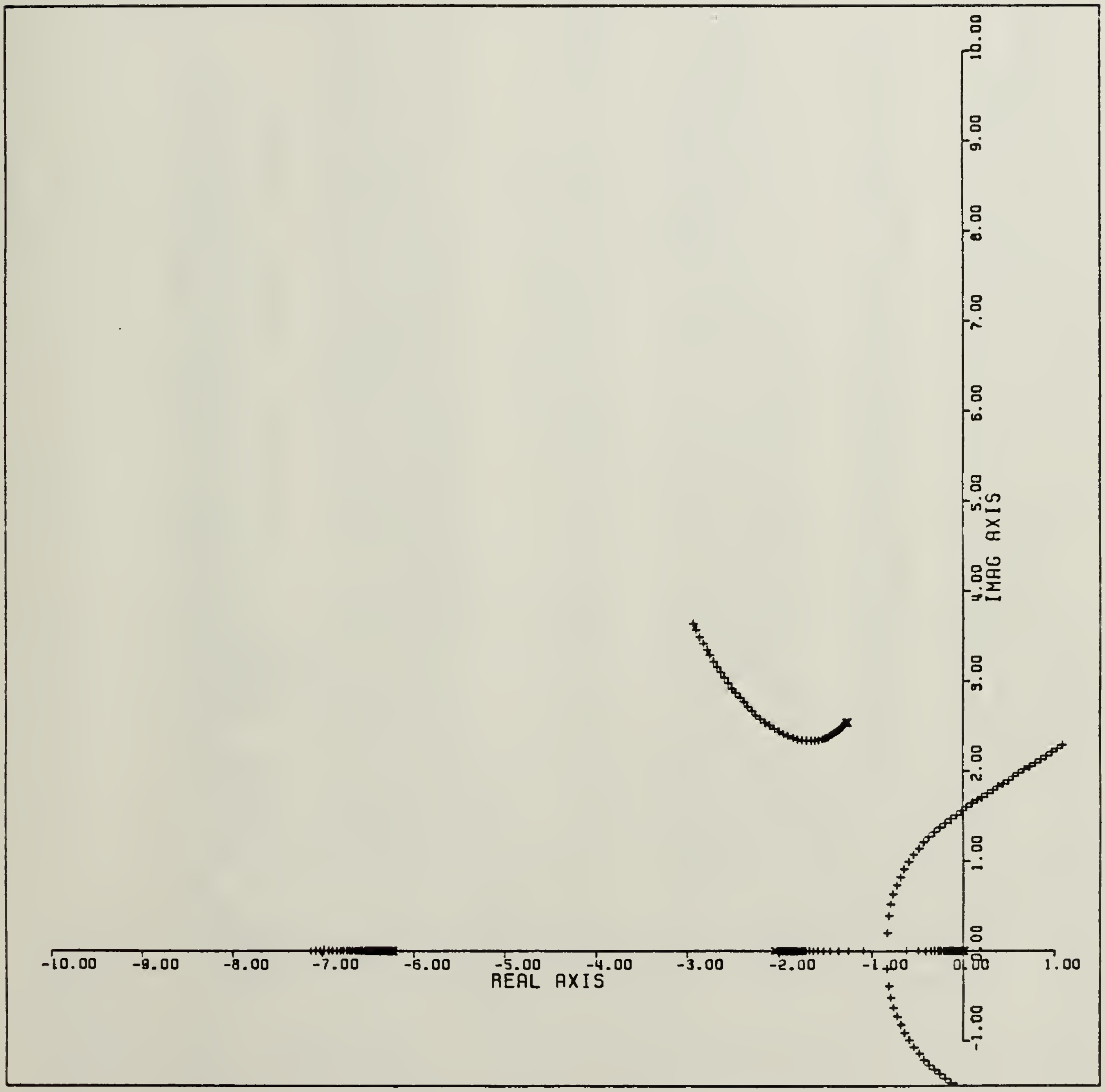
ROOT LOCUS OF ALTITUDE HOLDCOMMAND
FOR OUTER LOOP AUTOPILOT DESIGN



REAL AXIS (UNITS PER INCH) = 1.0000
IMAG AXIS (UNITS PER INCH) = 1.0000

ROOT LOCUS OF ALTITUDE HOLDCOMMAND FOR OUTER LOOP AUTOPILOT DESIGN



APPENDIX D

BASELINE GUIDANCE LAW SIMULATION

```
//WAT1562 JOB (1562,0198),'THESIS2',CLASS=G
// EXEC CSMPXV
//X.PLOTPARM DD *
 &PLOT SCALE=.5 &END
//X.SYSIN DD *
*
*     NOTE: 2  DEGREES=.034906585RADIANS   10 DEG=.1745329252
*     NONLINEAR BANK TO TURN CRUISE MISSLE (VARYING COEFFICIENTS)
*     WITH BANK TO TURN OR POLAR COORDINATE SYS GUIDANCE LAW
*     SEA SKIMMER GUIDANCE SCHEME
      LABEL NCGLINT,LAMDA=4.0,ECM=2.0 CPS,ROLL RATE=100 DEG/SEC
      LABEL BURNTHROUGH  400 FEET
      INITIAL
      PARAM G=32.17,T=242.3,WT=2200.0,S=12.0,K2=57.29577951,M=68.38,...
      C=0.0,KR1=0.28,KA1=0.05,KR2=0.10,KD=10.8,KR3=0.40,KA2=0.25,...
      KGAMMA=1.0,KFA=1.25,KFE1=1.0,KFE2=2.0,LAMDAZ=4.00,LAMDEL=4.0,...
      KALT=0.3,XTI=25000.0,YTI=0.0,HTI=10.0,CLIMBA=0.1500983,...
      PI=3.141592654,FREQ=2.00,SHIFTY=75.0,SHIFTH=15.0
* TABLE OF COEFFICIENTS STORED AS FUNCTION OF TWO OR THREE VARIABLES
*     TWO VARIABLE COEFFICIENT TABLES
*     LIFT CHARACTERISTICS
*     ALFA VS CLBASIC
      FUNCTION LIFT1=-12.0,-.32,-11.0,-.39,-10.0,-.46,-9.0,-.57,...
      -8.0,-.70,-7.0,-.69,-6.0,-.65,-5.0,-.58,-4.0,-.50,-3.0,-.42,...
      -2.0,-.30,-1.0,-.18,0.0,-.08,1.0,.04,2.0,.15,3.0,.25,4.0,.36,...
      5.0,.47,6.0,.58,7.0,.69,8.0,.80,9.0,.87,10.0,.78,11.0,.70,...
      12.0,.64
*     ELE VS DELTA CLST(ELE)
      FUNCTION LIFT2=-15.0,-.100,-14.0,-.097,-13.0,-.094,-12.0,...
      -.090,-11.0,-.084,-10.0,-.078,-9.0,-.071,-8.0,-.065,-7.0,...
      -.056,-6.0,-.048,-5.0,-.040,-4.0,-.032,-3.0,-.024,-2.0,-.016,...
      -1.0,-.008,0.0,0.0,1.0,.008,2.0,.016,3.0,.024,4.0,.033,5.0,...
      .041,6.0,.049,7.0,.057,8.0,.065,9.0,.073,10.0,.080,11.0,...
      .086,12.0,.092,13.0,.096,14.0,.098,15.0,.100
*     DRAG CHARACTERISTICS
*     CLBASIC VS CDBASIC
      FUNCTION DRAG1=-.9,.080,-.8,.061,-.7,.050,-.6,.042,-.5,.035,...
      -.4,.031,-.3,.026,-.2,.023,-.1,.022,0.0,.022,0.1,.023,0.2,...
      .024,0.3,.026,0.4,.031,0.5,.036,0.6,.042,0.7,.049,0.8,.057,...
      0.9,.068,1.0,.080
*     ELE VS DELTA CDST(ELE)
      FUNCTION DRAG2=-15.,.0106,-14.,.0091,-13.,.0077,-12.,.0065,...
      -10.,.0044,-9.,.0036,-8.,.0028,-7.,.0022,-6.,.0016,-5.,...
      .0011,-4.,.0007,-3.,.0003,-2.,.0001,-1.,0.,0.,0.,1.,.0001,2.,...
      .0004,3.,.0007,4.,.0011,5.,.0016,6.,.0023,7.,.0030,8.,.0039,9.,...
      .0049,10.,.0060,11.,.0073,12.,.0089,13.,.0106,14.,.0126,15.,.0146
*     AILERON VS DELTA CDST(AIL)
      FUNCTION DRAG3=-15.,.0120,-14.,.0102,-13.,.0085,-12.,.0071,...
```

```
      -10.,.0048,-9.,.0038,-8.,.0030,-7.,.0023,-6.,.0016,-5.,.0011,...        THE00490
      -4.,.0007,-3.,.0003,-2.,.0001,-1.,.0,.0,.0,1.,.0,2.,.0001,3.,...        THE00500
      .0003,4.,.0007,5.,.0011,6.,.0017,7.,.0023,8.,.0030,9.,.0038,...         THE00510
      10.,.0048,11.,.0039,12.,.0071,13.,.0085,14.,.0100,15.,.0120             THE00520
*     RUDDER VS DELTA CDST(RUD)                                               THE00530
      FUNCTION DRAG4=-15.,.0059,-14.,.0054,-13.,.0048,-12.,.0043,...          THE00540
      -10.,.0032,-9.,.0027,-8.,.0022,-7.,.0017,-6.,.0013,-5.,.0009,...        THE00550
      -4.,.0006,-3.,.0003,-2.,.0002,-1.,.0001,0.0,0.0,1.,.0001,2.,...         THE00560
      .0001,4.,.0006,5.,.0009,6.,.0013,7.,.0017,8.,.0022,9.,.0027,...         THE00570
      10.,.0032,11.,.0037,12.,.0043,13.,.0048,14.,.0054,15.,.0059             THE00580
*     PITCHING MOMENT CHARACTERISTICS                                         THE00590
*     ALFA VS CMBASIC                                                         THE00600
      FUNCTION PITCH1=-10.,1.13,-8.,.80,-6.,.50,-4.,.31,-2.,.16,...           THE00610
      0.,.08,2.,-.03,4.,-.13,6.,-.22,8.,-.32,10.,-.46,12.,-.62                THE00620
*     ELE VS DELTA CMST(ELE)                                                  THE00630
      FUNCTION PITCH2=-15.,.90,-14.,.88,-12.,.78,-10.,.68,-8.,.56,...         THE00640
      -6.,.42,-4.,.27,-2.,.12,0.,0.,2.,-.10,4.,-.20,6.,-.32,8.,-.45,...       THE00650
      10.,-.58,12.,-.69,14.,-.78,15.,-.80                                     THE00660
*                                                                             THE00670
*     THREE VARIABLE COEFFICIENT TABLES                                       THE00680
*     SIDESLIP CHARACTERISTICS                                                THE00690
*     ALFA VS BETA VS CYBASIC                                                 THE00700
      FUNCTION SIDE1,-8.0=(-8.,.148),(-6.,.111),(-4.,.073),(-2,...            THE00710
      .034),(0.0,-.002),(2.,-.040),(4.,-.077),(6.,-.114),(8.,-.151)           THE00720
      FUNCTION SIDE1,-6.0=(-8.,.149),(-6.,.110),(-4.,.072),(-2.,...           THE00730
      .034),(0.0,-.003),(2.,-.042),(4.,-.078),(6.,-.116),(8.,-.153)           THE00740
      FUNCTION SIDE1,4.0=(-8.,.140),(-6.,.100),(-4.,.063),(-2.,...            THE00750
      .025),(0.0,-.013),(2.,-.050),(4.,-.089),(6.,-.127),(8.,-.162)           THE00760
      FUNCTION SIDE1,8.0=(-8.,.137),(-6.,.077),(-4.,.060),(-2.,...            THE00770
      .022),(0.0,-.020),(2.,-.060),(4.,-.096),(6.,-.129),(8.,-.162)           THE00780
*     ALFA VS BETA VS CROLLBASIC                                              THE00790
      FUNCTION SIDE2,-8.0=(-8.,.0048),(-6.,.0038),(-4.,.0026),(-2.,...        THE00800
      .0014),(0.0,.0004),(2.,-.0005),(4.,-.0016),(6.,-.0030),(8.,...          THE00810
      -.0044)                                                                 THE00820
      FUNCTION SIDE2,2.0=(-8.,.0046),(-6.,.0036),(-4.,.0022),(-2.,...         THE00830
      .0010),(0.0,-.0004),(2.,-.0014),(4.,-.0026),(6.,-.0038),(8.,...         THE00840
      -.0052)                                                                 THE00850
      FUNCTION SIDE2,6.0=(-8.,.0038),(-6.,.0026),(-4.,.0013),(-2.,...         THE00860
      .0002),(0.0,-.0001),(2.,-.0025),(4.,-.0036),(6.,-.0047),(8.,...         THE00870
      -.0059)                                                                 THE00880
      FUNCTION SIDE2,10.=(-8.,.0044),(-6.,.0030),(-4.,.0020),(-2.,...         THE00890
      .0008),(0.0,-.0002),(2.,-.0014),(4.,-.0025),(6.,-.0036),(8.,...         THE00900
      -.0048)                                                                 THE00910
*     ALFA VS BETA VS CNBASIC                                                 THE00920
      FUNCTION SIDE3, -8.0=(-8.,-.034),(-6.,-.025),(-4.,-.016),...            THE00930
      (-2.,-.007),(0.,.001),(2.,.010),(4.,.019),(6.,.028),(8.,.036)           THE00940
      FUNCTION SIDE3, 0.0=(-8.,-.037),(-6.,-.028),(-4.,-.019),...             THE00950
      (-2.,-.009),(0.,-.001),(2.,.009),(4.,.018),(6.,.026),(8.,.034)          THE00960
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    FUNCTION SIDE3, 6.0=(-8.,-.042),(-6.,-.033),(-4.,-.022),...                THE00970
    (-2.,-.012),(0.,-.005),(2.,.008),(4.,.016),(6.,.024),(8.,.032)              THE00980
    FUNCTION SIDE3, 8.0=(-8.,-.042),(-6.,-.033),(-4.,-.023),...                 THE00990
    (-2.,-.014),(0.,-.008),(2.,.010),(4.,.016),(6.,.024),(8.,.032)              THE01000
*   DIRECTIONAL CONTROL CHARACTERISTICS                                          THE01010
*   ALFA VS RUDDER VS DELTA CYST(RUD)                                            THE01020
    FUNCTION DIREC1,-8.0=(-15.,-.090),(-10.,-.060),(-5.,-.032),...              THE01030
    (0.0,.004),(5.,.040),(10.,.070),(15.,.100)                                   THE01040
    FUNCTION DIREC1, 2.0=(-15.,-.097),(-10.,-.062),(-5.,-.036),...              THE01050
    (0.0,-.002),(5.,.042),(10.,.066),(15.,.098)                                  THE01060
    FUNCTION DIREC1, 6.0=(-15.,-.095),(-10.,-.062),(-5.,-.037),...              THE01070
    (0.0,-.006),(5.,.038),(10.,.062),(15.,.092)                                  THE01080
    FUNCTION DIREC1, 8.0=(-15.,-.102),(-10.,-.069),(-5.,-.042),...              THE01090
    (0.0,-.010),(5.,.040),(10.,.066),(15.,.096)                                  THE01100
*   ALFA VS RUDDER VS DELTA CNST(RUD)                                            THE01110
    FUNCTION DIREC2,-8.0=(-15.,.070),(-10.,.050),(-5.,.026),...                 THE01120
    (0.0,0.0),(5.,-.022),(10.,-.052),(15.,-.080)                                 THE01130
    FUNCTION DIREC2, 2.0=(-15.,.068),(-10.,.049),(-5.,.024),...                 THE01140
    (0.0,0.0),(5.,-.020),(10.,-.048),(15.,-.079)                                 THE01150
    FUNCTION DIREC2, 6.0=(-15.,.062),(-10.,.048),(-5.,.022),...                 THE01160
    (0.0,-.001),(5.,-.018),(10.,-.047),(15.,-.074)                               THE01170
    FUNCTION DIREC2, 8.0=(-15.,.065),(-10.,.048),(-5.,.018),...                 THE01180
    (0.0,-.003),(5.,-.014),(10.,-.046),(15.,-.075)                               THE01190
*   ALFA VS RUDDER VS DELTA CROLLST(RUD)                                         THE01200
    FUNCTION DIREC3,-8.0=(-15.,-.0050),(-10.,-.0034),(-5.,-.0018),...           THE01210
    (0.0,.0004),(5.,.0024),(10.,.0048),(15.,.0070)                               THE01220
    FUNCTION DIREC3, 2.0=(-15.,-.0038),(-10.,-.0029),(-5.,-.0018),...           THE01230
    (0.0,0.0),(5.,.0012),(10.,.0028),(15.,.0053)                                 THE01240
    FUNCTION DIREC3, 4.0=(-15.,-.0033),(-10.,-.0027),(-5.,-.0018),...           THE01250
    (0.0,-.0004),(5.,0.),(10.,.0012),(15.,.0040)                                 THE01260
    FUNCTION DIREC3, 7.0=(-15.,-.002),(-10.,-.002),(-5.,-.002),...              THE01270
    (0.,-.002),(5.,-.002),(10.,-.002),(15.,-.002)                                THE01280
    FUNCTION DIREC3, 8.0=(-15.,-.0014),(-10.,-.0018),(-5.,-.0020),...           THE01290
    (0.,-.0032),(5.,-.0038),(10.,-.0041),(15.,-.0048)                            THE01300
*   LATERAL CONTROL CHARACTERISTICS                                              THE01310
*   ALFA VS AILERON VS DELTA CYST(AIL)                                           THE01320
    FUNCTION LATRL1, -8.0=(-15.,.015),(-10.,.013),(-5.,.010),...                THE01330
    (0.,.007),(5.,.002),(10.,-.005),(15.,-.010)                                  THE01340
    FUNCTION LATRL1, -1.0=(-15.,.019),(-10.,.014),(-5.,.009),...                THE01350
    (0.,.002),(5.,-.003),(10.,-.009),(15.,-.014)                                 THE01360
    FUNCTION LATRL1,  4.0=(-15.,.017),(-10.,.010),(-5.,.002),...                THE01370
    (0.,-.007),(5.,-.014),(10.,-.020),(15.,-.025)                                THE01380
    FUNCTION LATRL1, 10.0=(-15.,.006),(-10.,-.002),(-5.,-.010),...              THE01390
    (0.,-.018),(5.,-.026),(10.,-.033),(15.,-.042)                                THE01400
*   ALFA VS AILERON VS DELTA CNST(AIL)                                           THE01410
    FUNCTION LATRL2, -8.0=(-15.,.0075),(-10.,.0040),(-5.,.0015),...             THE01420
    (0.,-.0020),(5.,-.0070),(10.,-.0120),(15.,-.0175)                            THE01430
    FUNCTION LATRL2, -4.0=(-15.,.0050),(-10.,.0030),(-5.,.0020),...             THE01440
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      (0.,-.0010),(5.,-.0030),(10.,-.0045),(15.,-.0070)                THE01450
      FUNCTION LATRL2, 0.0=(-15.,0.),(-10.,0.),(-5.,0.),(0.,0.),...    THE01460
      (5.,0.),(10.,0.),(15.,0.)                                        THE01470
      FUNCTION LATRL2, 4.0=(-15.,-.0075),(-10.,-.0050),(-5.,-.0025),...THE01480
      (0.0,-.0008),(5.,.0025),(10.,.0040),(15.,.0070)                  THE01490
      FUNCTION LATRL2, 8.0=(-15.,-.0120),(-10.,-.0085),(-5.,-.0060),...THE01500
      (0.0,-.0020),(5.,.0050),(10.,.0120),(15.,.0175)                  THE01510
*     ALFA VS AILERON VS DELTA CROLLST(AIL)                            THE01520
      FUNCTION LATRL3, -8.0=(-15.,.0087),(-10.,.0060),(-5.,.0030),...  THE01530
      (0.,.0004),(5.,-.0008),(10.,-.0018),(15.,-.0030)                 THE01540
      FUNCTION LATRL3, -4.0=(-15.,.0096),(-10.,.0066),(-5.,.0033),...  THE01550
      (0.,.0004),(5.,-.0023),(10.,-.0059),(15.,-.0080)                 THE01560
      FUNCTION LATRL3,  0.0=(-15.,.0100),(-10.,.0068),(-5.,.0034),...  THE01570
      (0.0,.0004),(5.,-.0030),(10.,-.0072),(15.,-.0092)                THE01580
      FUNCTION LATRL3,  4.0=(-15.,.0092),(-10.,.0064),(-5.,.0036),...  THE01590
      (0.0,-.0004),(5.,-.0030),(10.,-.0046),(15.,-.0088)               THE01600
      FUNCTION LATRL3,  8.0=(-15.,.0084),(-10.,.0058),(-5.,.0030),...  THE01610
      (0.0,-.0004),(5.,-.0020),(10.,-.0040),(15.,-.0050)               THE01620
*                                                                      THE01630
      DYNAMIC                                                          THE01640
      NOSORT                                                           THE01650
      IF (TIME.EQ.0.0) RNGMIN =100.0                                   THE01660
      IF (RNGMIN.LE.RANGE) GO TO 10                                    THE01670
         RNGMIN = RANGE                                                THE01680
         TIMMIN = TIME                                                 THE01690
         DXTGTM = DXTGT                                                THE01700
         DYTGTM = DYTGT                                                THE01710
         DZTGTM = DZTGT                                                THE01720
 10   CONTINUE                                                         THE01730
*     ALGORITHM THAT PROCEEDS FROM INGRESS TO 3000,THEN ATTACK UNTIL   THE01740
*     HIT. IT ALLOWS ECM TO ACTIVATE FROM 3000-BURN THROUGH RANGE.     THE01750
         IF(RANGE.GT.3000.0) GO TO 20                                  THE01760
         IF(RANGE.GT.0.0) GO TO 60                                     THE01770
*     INGRESS INTO 3000.0 FEET                                         THE01780
 20            DXTGT = XT-XEARTH                                       THE01790
               DYTGT = YT-YEARTH                                       THE01800
               DZTGT = HT-ALTUDE                                       THE01810
               AYC = LAMDAZ*VT*SIGDZ1/G                                THE01820
               ANC = AZC*COS(PHI)+AYC*SIN(PHI)                         THE01830
               IF(AYC.EQ.0.0.AND.AZC.EQ.0.0) PHIC = 0.0                THE01840
               IF(AYC.NE.0.0.OR.AZC.NE.0.0) PHIC=ATAN2(AYC,AZC)        THE01850
               PHIC1 = LIMIT(-1.047,1.047,PHIC)                        THE01860
         GO TO 200                                                     THE01870
*     ATTACK PHASE INTO THE TARGET                                     THE01880
 60         IF (RANGE.GT.2900.) GO TO 65                               THE01890
            IF (RANGE.LT.400.0) GO TO 65                               THE01900
                                                                       THE01910
*     ALLOW ECM TO OCCUR BETWEEN 2900 AND BURN THROUGH RANGE           THE01920
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*     PUT ECM BLINKING OF 75FT HORIZONTAL SHIFT AT FREQ(.5,1,2 CPS)          THE01930
          Y1 = SIN(2*PI*FREQ*TIME)                                           THE01940
          YY = INSW(Y1,SHIFTY,0.0)                                           THE01950
          YTT = YT-YY                                                        THE01960
*     PUT ECM BLINKING OF 15FT VERTICAL SHIFT AT FREQ(.5,1,2 CPS)            THE01970
          H1 = SIN(2*PI*FREQ*TIME)                                           THE01980
          HH = INSW(H1,SHIFTH,0.0)                                           THE01990
          HTT = HT+HH                                                        THE02000
          DXTGT = XT-XEARTH                                                  THE02010
          DYTGT = YTT-YEARTH                                                 THE02020
          DZTGT = HTT-ALTUDE                                                 THE02030
          GO TC 66                                                           THE02040
 65       DXTGT = XT-XEARTH                                                  THE02050
          DYTGT = YT-YEARTH                                                  THE02060
          DZTGT = HT-ALTUDE                                                  THE02070
*     PROPORTIONAL ELEVATION                                                 THE02080
 66               PNEL1 = LAMDEL*VT*SIGDE1/G                                 THE02090
                  AZCPR3 = PNEL1 + 1.0                                       THE02100
                  AYC = LAMDAZ*VT*SIGDZ1/G                                   THE02110
                  ANC = AZCPR3*COS(PHI)+AYC*SIN(PHI)                         THE02120
                  PHIC1 = ATAN2(AYC,AZCPR3)                                  THE02130
*                 THIS ROUTINE KEEPS PHIC FROM ROTATING 360 DEG WHEN         THE02140
*                 TAN FUNCTION PASSES THROUGH 180 DEG.                       THE02150
                  DELTA =  PHIC1-PHI                                         THE02160
                  DELTA1 = ABS(DELTA)                                        THE02170
                  IF (DELTA1.LT.3.141592654) GO TO 200                       THE02180
                  IF (PHIC1.GE.0.0) GO TO 70                                 THE02190
                  PHIC1 = PHIC1 + 6.2831853                                  THE02200
                  GO TO 200                                                  THE02210
 70               PHIC1 = PHIC1 - 6.2831853                                  THE02220
 200  CONTINUE                                                               THE02230
      SORT                                                                   THE02240
      QS =12.0*.002377*(VT**2)/2                                             THE02250
      PHIDOT = P+TAN(THETA)*(Q*SIN(PHI)+R*COS(PHI))                          THE02260
      THETAD = Q*COS(PHI)-R*SIN(PHI)                                         THE02270
      SYDCT = (Q*SIN(PHI)+R*COS(PHI))/COS(THETA)                             THE02280
      PHI = INTGRL(0.0,PHIDOT)                                               THE02290
      THETA = INTGRL(0.04880,THETAD)                                         THE02300
      SY = INTGRL(0.0,SYDCT)                                                 THE02310
      UDOT = -G*SIN(THETA)+V*R-W*Q+X/M+T/M                                   THE02320
      VDOT = G*SIN(PHI)*COS(THETA)-U*R+W*P+Y/M                               THE02330
      WDOT = G*COS(PHI)*COS(THETA)+U*Q-V*P+Z/M                               THE02340
      U = INTGRL(838.1,UDOT)                                                 THE02350
      V = INTGRL(0.0,VDOT)                                                   THE02360
      W = INTGRL(38.79,WDOT)                                                 THE02370
      XEDCT= U*COS(SY)*COS(THETA)+V*(COS(SY)*SIN(THETA)*SIN(PHI)...          THE02380
      -SIN(SY)*COS(PHI))+W*(COS(SY)*SIN(THETA)*COS(PHI)+...                  THE02390
      SIN(SY)*SIN(PHI))                                                      THE02400
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      YEDOT=U*SIN(SY)*COS(THETA)+V*(SIN(SY)*SIN(THETA)*SIN(PHI)...     THE02410
      +COS(SY)*COS(PHI))+W*(SIN(SY)*SIN(THETA)*COS(PHI)-...            THE02420
      COS(SY)*SIN(PHI))                                                 THE02430
      ZEDOT= U*SIN(THETA)-V*COS(THETA)*SIN(PHI)-W*COS(THETA)*COS(PHI)  THE02440
      XEARTH=INTGRL(0.0,XEDOT)                                          THE02450
      YEARTH=INTGRL(0.0,YEDOT)                                          THE02460
*     NOTE: ALTUDE AND Z FUNCTIONS ARE DEFINED AS POSITIVE GOING UP     THE02470
      ALTUDE=INTGRL(50.,ZEDOT)                                          THE02480
      PDOT = 0.036089*LA+0.000279*NA+0.009160*P*Q-0.183711*R*Q          THE02490
      RDOT = 0.000279*LA+0.000664*NA-0.978236*P*Q-0.009160*R*Q          THE02500
      QDOT = (MA+1484.2*P*R-11.7*(P**2-R**2))/1507.0                    THE02510
      P = INTGRL(0.0,PDOT)                                              THE02520
      Q = INTGRL(0.0,QDOT)                                              THE02530
      R = INTGRL(0.0,RDOT)                                              THE02540
      ALFA=ATAN(W/U)                                                    THE02550
      BETA=ASIN(V/VT)                                                   THE02560
      ALFADT=DERIV(0.04880,ALFA)                                        THE02570
      BETADT=DERIV(0.0,BETA)                                            THE02580
      VT=SQRT(U**2+V**2+W**2)                                           THE02590
      CLBAS=FUNGEN(LIFT1,1,ALFA1)                                       THE02600
      DCLSTE=FUNGEN(LIFT2,1,ELE1)                                       THE02610
      CDBAS=FUNGEN(DRAG1,1,CLBAS)                                       THE02620
      DCDSTE=FUNGEN(DRAG2,1,ELE1)                                       THE02630
      DCDSTA=FUNGEN(DRAG3,1,AIL1)                                       THE02640
      DCDSTR=FUNGEN(DRAG4,1,RUD1)                                       THE02650
      CMBAS=FUNGEN(PITCH1,1,ALFA1)                                      THE02660
      DCMSTE=FUNGEN(PITCH2,1,ELE1)                                      THE02670
      CYBAS=TWOVAR(SIDE1,BETA1,ALFA1)                                   THE02680
      CRBAS=TWOVAR(SIDE2,BETA1,ALFA1)                                   THE02690
      CNBAS=TWOVAR(SIDE3,BETA1,ALFA1)                                   THE02700
      DCYSTR=TWOVAR(DIREC1,RUD1,ALFA1)                                  THE02710
      DCNSTR=TWOVAR(DIREC2,RUD1,ALFA1)                                  THE02720
      DCRSTR=TWOVAR(DIREC3,RUD1,ALFA1)                                  THE02730
      DCYSTA=TWOVAR(LATRL1,AIL1,ALFA1)                                  THE02740
      DCNSTA=TWOVAR(LATRL2,AIL1,ALFA1)                                  THE02750
      DCRSTA=TWOVAR(LATRL3,AIL1,ALFA1)                                  THE02760
      CL=CLBAS+DCLSTE+.707/VT*(2.0*ALFADT+5.0*Q)                        THE02770
      CD=CDBAS+DCDSTE+DCDSTA+DCDSTR+.707/VT*(0.1*ALFADT+0.1*Q)          THE02780
      CY=CYBAS+DCYSTR+DCYSTA+4.24/VT*(0.40*R-0.10*P-0.10*BETADT)        THE02790
      CM=CMBAS+DCMSTE+0.707/VT*(-10.0*ALFADT-15.0*Q)                    THE02800
      CN=CNBAS+DCNSTR+DCNSTA+4.24/VT*(0.15*BETADT-0.20*R-0.01*P)        THE02810
      CROLL=CRBAS+DCRSTA+DCRSTR+4.24/VT*(0.20*R-0.40*P)                 THE02820
      L=CL*QS                                                           THE02830
      D=CD*QS                                                           THE02840
      LA=8.485*CROLL*QS                                                 THE02850
      MA=1.414*CM*QS                                                    THE02860
      NA=8.485*CN*QS                                                    THE02870
      X=L*SIN(ALFA)-D*COS(ALFA)                                         THE02880
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      Y=CY*QS                                                          THE02890
      Z=-L*COS(ALFA)-D*SIN(ALFA)                                       THE02900
      NZLOAD=-Z/(M*G)                                                  THE02910
      NYLOAD=Y/(M*G)                                                   THE02920
      ALFA1=ALFA*K2                                                    THE02930
      BETA1=BETA*K2                                                    THE02940
      PHI1=PHI*K2                                                      THE02950
      THETA1=THETA*K2                                                  THE02960
      P1=P*K2                                                          THE02970
      Q1=Q*K2                                                          THE02980
      R1=R*K2                                                          THE02990
      SY1=SY*K2                                                        THE03000
      ELE1=ELE*K2                                                      THE03010
      RUD1=RUD*K2                                                      THE03020
      AIL1=AIL*K2                                                      THE03030
      GAMMA1=GAMMA*K2                                                  THE03040
*                                                                      THE03050
*     INNER LOOP AUTOPILOT                                             THE03060
*                                                                      THE03070
*     NORMAL ACCELERATION COMMAND                                      THE03080
*                                                                      THE03090
      ANC1 = LIMIT(-2.0,4.0,ANC)                                       THE03100
      ERRORN = ANC1-(NZLOAD+C*QDOT/G)                                  THE03110
      NSERVI =-1.0*(KA1* INTGRL(0.0,ERRORN)-KR1*Q)                     THE03120
      NSERVO = REALPL(0.0,0.025,NSERVI)                                THE03130
      ELE = LIMIT(-0.262,0.262,NSERVO)                                 THE03140
*                                                                      THE03150
*     BANK ANGLE COMMAND SYSTEM                                        THE03160
*     60 DEGREE LIMIT ON BANK ANGLE = 1.047 RADIANS(DONE IN ALGORITHM) THE03170
*     ROLL RATE (PCL) IS VARIED AS 50,100,&200 DEG/SEC                 THE03180
*     50=.87,  100=1.75,  200=3.49                                     THE03190
*                                                                      THE03200
      ERRBA1 = (PHIC1-PHI)*KD                                          THE03210
      PCL = LIMIT(-1.75,1.75,ERRBA1)                                   THE03220
      PCL1 = PCL*K2                                                    THE03230
      PHIC2 = PHIC1*K2                                                 THE03240
      BASRVI = -1.0*KR2*(PCL-P)                                        THE03250
      BASRVO = REALPL(0.0,0.025,BASRVI)                                THE03260
      AIL = LIMIT(-0.262,0.262,BASRVO)                                 THE03270
*                                                                      THE03280
*     TURN COORDINATOR                                                 THE03290
*                                                                      THE03300
      ALC = 0.0                                                        THE03310
      EN = ALC-(C*RDOT/G+NYLOAD)                                       THE03320
      EN1= KA2*(INTGRL(0.0,EN))                                        THE03330
      TSERVI = -1.0*(EN1-KR3*R)                                        THE03340
      TSERVO = REALPL(0.0,0.025,TSERVI)                                THE03350
      RUD = LIMIT(-0.262,0.262,TSERVO)                                 THE03360
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*                                                                       THE03370
*     GUIDANCE.                                                         THE03380
*                                                                       THE03390
*     GUIDANCE SCHEME IS DIVIDED INTO TWO PHASES-INGRESS AND ATTACK,    THE03400
*     PROPORTIONAL NAVIGATION IS USED FOR HEADING CONTROL DURING INGRESSTHE03410
*     (WITH BANK ANGLE LIMITED TO 60 DEG)AND DURING ATTACK PHASE        THE03420
*     (BANK ANGLE UNLIMITED).                                           THE03430
*     AN ALTITUDE HOLD OF 50 FEET IS USED FOR INGRESS PHASE.            THE03440
*     PROPORTIONAL NAVIGATION IN ELEVATION IS USED DURING ATTACK PHASE. THE03450
*                                                                       THE03460
*     OUTER LOOP AUTOPILOT                                              THE03470
*                                                                       THE03480
*     FLIGHT PATH ANGLE                                                 THE03490
      AZC = 1.0+KGAMMA*VT/G*(GAMMAC-GAMMA)                              THE03500
      GAMMA = ASIN(ZEDOT/VT)                                            THE03510
*     ALTITUDE HOLD                                                     THE03520
      ALTCMD = 50.0                                                     THE03530
      GAMMAC = KALT/VT*(ALTCMD-ALTUDE)                                  THE03540
*                                                                       THE03550
*     SEEKER EQUATIONS                                                  THE03560
*                                                                       THE03570
      YT2 = YTI+35.0*TIME                                               THE03580
      RANGE  = SQRT((XTI-XEARTH)**2+(YT2-YEARTH)**2+(HTI-ALTUDE)**2)    THE03590
      SIGDZB = -SIGDEL*SIN(PHI)+SIGDAZ*COS(THETA)*COS(PHI)              THE03600
      SIGDEB = SIGDEL*COS(PHI)+SIGDAZ*COS(THETA)*SIN(PHI)               THE03610
      SIGDZ1 = SIGDZB*COS(PHI)+SIGDEB*SIN(PHI)                          THE03620
      SIGDE1 = -SIGDZB*SIN(PHI)+SIGDEB*COS(PHI)                         THE03630
*     THIS SECTION CHANGES PROGRAM VARIABLES TO MORE COMMON NAMES       THE03640
      XRANGE = ABS(XTI-XEARTH)                                          THE03650
      YRANGE = ABS(YT2-YEARTH)                                          THE03660
      ZRANGE = ABS(HTI-ALTUDE)                                          THE03670
      PCMD = PCL1                                                       THE03680
      PHICMD = PHIC2                                                    THE03690
      XMISLE = XEARTH                                                   THE03700
      YMISLE = YEARTH                                                   THE03710
      HMISLE = ALTUDE                                                   THE03720
      XTGT = XTI                                                        THE03730
      YTGT = YT2                                                        THE03740
      HTGT = HTI                                                        THE03750
      YECM = YTT                                                        THE03760
      HECM = HTT                                                        THE03770
      RUDDER = RUD1                                                     THE03780
      L1STAB = ELE1-AIL1                                                THE03790
      R1STAB = ELE1+AIL1                                                THE03800
      NZ = NZLOAD                                                       THE03810
      NZ1CMD = ANC1                                                     THE03820
      NY = NYLOAD                                                       THE03830
      NY1CMD = ALC                                                      THE03840
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      ELLCSR = SIGDEL*K2                                                THE03850
      AZLCSR = SIGDAZ*K2                                                THE03860
*                                                                       THE03870
      THETDT = (-ZEDOT*(DXTGT**2+DYTGT**2)-DZTGT*(-XEDOT*DXTGT+...      THE03880
      (35.0-YEDOT)*DYTGT))/(RANGE**2*SQRT(DXTGT**2+DYTGT**2))           THE03890
      THETDF = REALPL(0.0,10.,THETAD)                                   THE03900
      SIGDEL = THETDT-THETDF                                            THE03910
      SYDOTT =(XEDOT*DYTGT+(35.-YEDOT)*DXTGT)/(DXTGT**2+DYTGT**2)       THE03920
      SYDOTF = REALPL(0.0,10.0,SYDOT)                                   THE03930
      SIGDAZ = SYDOTT-SYDOTF                                            THE03940
*                                                                       THE03950
*     TARGET GLINT FACTOR WITH SHIP MOVING AT 21 KNOTS TO EAST          THE03960
*     YTR= GAUSS(5,0.0,20.0)                                            THE03970
*     XTR = GAUSS(3,0.0,6.0)                                            THE03980
*     HTR = GAUSS(1,0.0,6.0)                                            THE03990
*     XT  = XTI+XTR                                                     THE04000
*     YT  = YT2+YTR                                                     THE04010
*     HT  = HTI+HTR                                                     THE04020
      XT  = XTI                                                         THE04030
      YT  = YT2                                                         THE04040
      HT  = HTI                                                         THE04050
*                                                                       THE04060
      NOSCRT                                                            THE04070
      CALL DEBUG(1,29.82)                                               THE04080
      CALL DEBUG(1,29.84)                                               THE04090
      CALL DEBUG(1,29.86)                                               THE04100
      CALL DEBUG(1,29.88)                                               THE04110
      CALL DEBUG(1,29.90)                                               THE04120
      CALL DEBUG(1,29.95)                                               THE04130
      TERMINAL                                                          THE04140
      OUTPUT TIMMIN,RNGMIN,DXTGTM,DYTGTM,DZTGTM                         THE04150
      LABEL MINIMUM RANGE,DXTGT,DYTGT, & DZTGT AND TIME OF MIN RANGE    THE04160
      PAGE NPLOT=5                                                      THE04170
      TIMER FINTIM=31.00, OUTDEL=0.100, DELT=0.01925                    THE04180
      OUTPUT TIME,P1(-200.0,200.0),PCMD(-200.0,200.0)                   THE04190
      LABEL ROLL RATE (DEG/SEC) VS TIME                                 THE04200
      PAGE XYPLOT                                                       THE04210
      OUTPUT TIME,PHI1(-180.0,180.0),PHICMD(-180.0,180.0)               THE04220
      LABEL BANK ANGLE (DEGREES) VS TIME                                THE04230
      PAGE XYPLOT                                                       THE04240
      OUTPUT TIME,RANGE(-4000.,28000.),XRANGE(-4000.,28000.),...        THE04250
      YRANGE(-400.,2800.),ZRANGE(-40.,280.)                             THE04260
      LABEL RANGE,XRANGE,YRANGE,ZRANGE (FEET) VS TIME                   THE04270
      PAGE XYPLOT                                                       THE04280
*     OUTPUT TIME(29.5,30.5),RANGE(0.,800.),XRANGE(0.,80.),...          THE04290
*     YRANGE(0.,80.),ZRANGE(0.,80.)                                     THE04300
*     LABEL RANGE,XRANGE,YRANGE,ZRANGE (FEET) VS TIME                   THE04310
*     PAGE XYPLOT                                                       THE04320
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*       OUTPUT TIME,XMISLE(0.,32000.0),XTGT(0.,32000.0)                  THE04330
*       LABEL MISSILE AND TARGET X COORDINATE (FEET) VS TIME             THE04340
*       PAGE XYFLOT                                                      THE04350
*     OUTPUT TIME,YMISLE(-400.,2800.),YTGT(-400.,2800.),YECM(-400.,2800.) THE04360
*       LABEL MISSILE AND TARGET Y COORDINATE (FEET) VS TIME             THE04370
*       PAGE XYFLOT                                                      THE04380
*       OUTPUT TIME,HMISLE(-40.,280.),HTGT(-40.,280.),HECM(-40.,280.)    THE04390
*       LABEL MISSILE AND TARGET ALTITUDE (FEET) VS TIME                 THE04400
*       PAGE XYFLOT                                                      THE04410
        OUTPUT TIME,LISTAB(-20.,20.),RISTAB(-20.,20.)                    THE04420
        LABEL LEFT & RIGHT STABILIZERS (DEGREES) VS TIME                 THE04430
        PAGE XYFLOT                                                      THE04440
        OUTPUT TIME,RUDDER(-20.,20.)                                     THE04450
        LABEL RUDDER POSITION (DEGREES) VS TIME                          THE04460
        PAGE XYFLOT                                                      THE04470
*       OUTPUT TIME,NZ(-3.,5.),NZ1CMD(-3.,5.)                            THE04480
*       LABEL VERTICAL ACCELERATION (G'S) VS TIME                        THE04490
*       PAGE XYFLOT                                                      THE04500
*       OUTPUT TIME,NY(-2.,2.),NY1CMD(-2.,2.)                            THE04510
*       LABEL HORIZONTAL ACCELERATION (G'S) VS TIME                      THE04520
*       PAGE XYFLOT                                                      THE04530
*       OUTPUT TIME,ELLOSR,AZLOSR                                        THE04540
*       LABEL SEEKER EARTH LINE OF SIGHT RATES (DEG/SEC) VS TIME         THE04550
*       PAGE XYFLOT                                                      THE04560
        OUTPUT XMISLE(21000.,25000.),YMISLE(0.,2000.),HMISLE(0.,800.)    THE04570
        LABEL MAP OF YMISLE AND HMISLE VS XMISLE  (FEET)                 THE04580
        PAGE XYFLOT                                                      THE04590
        END                                                              THE04600
        STOP                                                             THE04610
ENDJOB                                                                   THE04620
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APPENDIX E

SEA SKIMMER GUIDANCE LAW SIMULATION

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//WAT1562 JOB (1562,0198),'THESIS2',CLASS=G                               THE00010
// EXEC CSMPXV                                                            THE00020
//X.PLOTPARM DD *                                                         THE00030
 &PLOT SCALE=.5 &END                                                      THE00040
//X.SYSIN DD *                                                            THE00050
*                                                                         THE00060
*     NOTE: 2  DEGREES=.034906585RADIANS  10 DEG=.1745329252              THE00070
*     NONLINEAR BANK TO TURN CRUISE MISSLE (VARYING COEFFICIENTS)         THE00080
*     WITH BANK TO TURN OR POLAR COORDINATE SYS GUIDANCE LAW              THE00090
*     BASE LINE GLIDANCE LAW                                              THE00100
      LABEL NOGLINT,LAMDA=4.0,ECM=0.5 CPS,ROLL RATE=100 DEG/SEC           THE00110
      LABEL BURNTHROUGH 2000 FEET                                         THE00120
      INITIAL                                                             THE00130
      PARAM G=32.17,T=242.3,WT=2200.0,S=12.0,K2=57.29577951,M=68.38,...   THE00140
      C=0.0,KR1=0.28,KA1=0.05,KR2=0.10,KD=10.8,KR3=0.40,KA2=0.25,...      THE00150
      KGAMMA=1.0,KFA=1.25,KFE1=1.0,KFE2=2.0,LAMDAZ=4.00,LAMDEL=4.0,...    THE00160
      KALT=0.3,XTI=25000.0,YTI=0.0,HTI=10.0,CLIMBA=0.1500983,...          THE00170
      PI=3.141592654,FREQ=0.50,SHIFTY=75.0,SHIFTH=15.0                    THE00180
* TABLE OF COEFFICIENTS STORED AS FUNCTION OF TWO OR THREE VARIABLES      THE00190
*     TWO VARIABLE COEFFICIENT TABLES                                     THE00200
*     LIFT CHARACTERISTICS                                                THE00210
*     ALFA VS CLBASIC                                                     THE00220
      FUNCTION LIFT1=-12.0,-.32,-11.0,-.39,-10.0,-.46,-9.0,-.57,...       THE00230
      -8.0,-.70,-7.0,-.69,-6.0,-.65,-5.0,-.58,-4.0,-.50,-3.0,-.42,...     THE00240
      -2.0,-.30,-1.0,-.18,0.0,-.08,1.0,.04,2.0,.15,3.0,.25,4.0,.36,...    THE00250
      5.0,.47,6.0,.58,7.0,.69,8.0,.80,9.0,.87,10.0,.78,11.0,.70,...       THE00260
      12.0,.64                                                            THE00270
*     ELE VS DELTA CLST(ELE)                                              THE00280
      FUNCTION LIFT2=-15.0,-.100,-14.0,-.097,-13.0,-.094,-12.0,...        THE00290
      -.090,-11.0,-.084,-10.0,-.078,-9.0,-.071,-8.0,-.065,-7.0,...        THE00300
      -.056,-6.0,-.048,-5.0,-.040,-4.0,-.032,-3.0,-.024,-2.0,-.016,...    THE00310
      -1.0,-.008,0.0,0.0,1.0,.008,2.0,.016,3.0,.024,4.0,.033,5.0,...      THE00320
      .041,6.0,.049,7.0,.057,8.0,.065,9.0,.073,10.0,.080,11.0,...         THE00330
      .086,12.0,.092,13.0,.096,14.0,.098,15.0,.100                        THE00340
*     DRAG CHARACTERISTICS                                                THE00350
*     CLBASIC VS CDBASIC                                                  THE00360
      FUNCTION DRAG1=-.9,.080,-.8,.061,-.7,.050,-.6,.042,-.5,.035,...     THE00370
      -.4,.031,-.3,.026,-.2,.023,-.1,.022,0.0,.022,0.1,.023,0.2,...       THE00380
      .024,0.3,.026,0.4,.031,0.5,.036,0.6,.042,0.7,.049,0.8,.057,...      THE00390
      0.9,.068,1.0,.080                                                   THE00400
*     ELE VS DELTA CDST(ELE)                                              THE00410
      FUNCTION DRAG2=-15.,.0106,-14.,.0091,-13.,.0077,-12.,.0065,...      THE00420
      -10.,.0044,-9.,.0036,-8.,.0028,-7.,.0022,-6.,.0016,-5.,...          THE00430
      .0011,-4.,.0007,-3.,.0003,-2.,.0001,-1.,0.,0.,0.,1.,.0001,2.,...    THE00440
      .0004,3.,.0007,4.,.0011,5.,.0016,6.,.0023,7.,.0030,8.,.0039,9.,...  THE00450
      .0049,10.,.0060,11.,.0073,12.,.0089,13.,.0106,14.,.0126,15.,.0146   THE00460
*     AILERON VS DELTA CDST(AIL)                                          THE00470
      FUNCTION DRAG3=-15.,.0120,-14.,.0102,-13.,.0085,-12.,.0071,...      THE00480
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        -10.,.0048,-9.,.0038,-8.,.0030,-7.,.0023,-6.,.0016,-5.,.0011,...   THE00490
        -4.,.0007,-3.,.0003,-2.,.0001,-1.,.0,.0,.0,1.,.0,2.,.0001,3.,...   THE00500
        .0003,4.,.0007,5.,.0011,6.,.0017,7.,.0023,8.,.0030,9.,.0038,...    THE00510
        10.,.0048,11.,.0059,12.,.0071,13.,.0085,14.,.0100,15.,.0120        THE00520
*       RUDDER VS DELTA CDST(RUD)                                          THE00530
        FUNCTION DRAG4=-15.,.0059,-14.,.0054,-13.,.0048,-12.,.0043,...     THE00540
        -10.,.0032,-9.,.0027,-8.,.0022,-7.,.0017,-6.,.0013,-5.,.0009,...   THE00550
        -4.,.0006,-3.,.0003,-2.,.0002,-1.,.0001,0.0,0.0,1.,.0001,2.,...    THE00560
        .0001,4.,.0006,5.,.0009,6.,.0013,7.,.0017,8.,.0022,9.,.0027,...    THE00570
        10.,.0032,11.,.0037,12.,.0043,13.,.0048,14.,.0054,15.,.0059        THE00580
*       PITCHING MOMENT CHARACTERISTICS                                    THE00590
*       ALFA VS CMBASIC                                                    THE00600
        FUNCTION PITCH1=-10.,1.13,-8.,.80,-6.,.50,-4.,.31,-2.,.16,...      THE00610
        0.,.08,2.,-.03,4.,-.13,6.,-.22,8.,-.32,10.,-.46,12.,-.62           THE00620
*       ELE VS DELTA CMST(ELE)                                             THE00630
        FUNCTION PITCH2=-15.,.90,-14.,.88,-12.,.78,-10.,.68,-8.,.56,...    THE00640
        -6.,.42,-4.,.27,-2.,.12,0.,0.,2.,-.10,4.,-.20,6.,-.32,8.,-.45,...  THE00650
        10.,-.58,12.,-.69,14.,-.78,15.,-.80                                THE00660
*                                                                          THE00670
*       THREE VARIABLE COEFFICIENT TABLES                                  THE00680
*       SIDESLIP CHARACTERISTICS                                           THE00690
*       ALFA VS BETA VS CYBASIC                                            THE00700
        FUNCTION SIDE1,-8.0=(-8.,.148),(-6.,.111),(-4.,.073),(-2.,...      THE00710
        .034),(0.0,-.002),(2.,-.040),(4.,-.077),(6.,-.114),(8.,-.151)      THE00720
        FUNCTION SIDE1,-6.0=(-8.,.149),(-6.,.110),(-4.,.072),(-2.,...      THE00730
        .034),(0.0,-.003),(2.,-.042),(4.,-.078),(6.,-.116),(8.,-.153)      THE00740
        FUNCTION SIDE1,4.0=(-8.,.140),(-6.,.100),(-4.,.063),(-2.,...       THE00750
        .025),(0.0,-.013),(2.,-.050),(4.,-.089),(6.,-.127),(8.,-.162)      THE00760
        FUNCTION SIDE1,8.0=(-8.,.137),(-6.,.077),(-4.,.060),(-2.,...       THE00770
        .022),(0.0,-.020),(2.,-.060),(4.,-.096),(6.,-.129),(8.,-.162)      THE00780
*       ALFA VS BETA VS CROLLBASIC                                         THE00790
        FUNCTION SIDE2,-8.0=(-8.,.0048),(-6.,.0038),(-4.,.0026),(-2.,...   THE00800
        .0014),(0.0,.0004),(2.,-.0005),(4.,-.0016),(6.,-.0030),(8.,...     THE00810
        -.0044)                                                            THE00820
        FUNCTION SIDE2,2.0=(-8.,.0046),(-6.,.0036),(-4.,.0022),(-2.,...    THE00830
        .0010),(0.0,-.0004),(2.,-.0014),(4.,-.0026),(6.,-.0038),(8.,...    THE00840
        -.0052)                                                            THE00850
        FUNCTION SIDE2,6.0=(-8.,.0038),(-6.,.0026),(-4.,.0013),(-2.,...    THE00860
        .0002),(0.0,-.0001),(2.,-.0025),(4.,-.0036),(6.,-.0047),(8.,...    THE00870
        -.0059)                                                            THE00880
        FUNCTION SIDE2,10.=(-8.,.0044),(-6.,.0030),(-4.,.0020),(-2.,...    THE00890
        .0008),(0.0,-.0002),(2.,-.0014),(4.,-.0025),(6.,-.0036),(8.,...    THE00900
        -.0048)                                                            THE00910
*       ALFA VS BETA VS CNBASIC                                            THE00920
        FUNCTION SIDE3, -8.0=(-8.,-.034),(-6.,-.025),(-4.,-.016),...       THE00930
        (-2.,-.007),(0.,.001),(2.,.010),(4.,.019),(6.,.028),(8.,.036)      THE00940
        FUNCTION SIDE3, 0.0=(-8.,-.037),(-6.,-.028),(-4.,-.019),...        THE00950
        (-2.,-.009),(0.,-.001),(2.,.009),(4.,.018),(6.,.026),(8.,.034)     THE00960
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      FUNCTION SIDE3, 6.0=(-8.,-.042),(-6.,-.033),(-4.,-.022),...        THE00970
      (-2.,-.012),(0.,-.005),(2.,.008),(4.,.016),(6.,.024),(8.,.032)     THE00980
      FUNCTION SIDE3, 8.0=(-8.,-.042),(-6.,-.033),(-4.,-.023),...        THE00990
      (-2.,-.014),(0.,-.008),(2.,.010),(4.,.016),(6.,.024),(8.,.032)     THE01000
*     DIRECTIONAL CONTROL CHARACTERISTICS                                THE01010
*     ALFA VS RUDDER VS DELTA CYST(RUD)                                  THE01020
      FUNCTION DIREC1,-8.0=(-15.,-.090),(-10.,-.060),(-5.,-.032),...     THE01030
      (0.0,.004),(5.,.040),(10.,.070),(15.,.100)                         THE01040
      FUNCTION DIREC1, 2.0=(-15.,-.097),(-10.,-.062),(-5.,-.036),...     THE01050
      (0.0,-.002),(5.,.042),(10.,.066),(15.,.098)                        THE01060
      FUNCTION DIREC1, 6.0=(-15.,-.095),(-10.,-.062),(-5.,-.037),...     THE01070
      (0.0,-.006),(5.,.038),(10.,.062),(15.,.092)                        THE01080
      FUNCTION DIREC1, 8.0=(-15.,-.102),(-10.,-.069),(-5.,-.042),...     THE01090
      (0.0,-.010),(5.,.040),(10.,.066),(15.,.096)                        THE01100
*     ALFA VS RUDDER VS DELTA CNST(RUD)                                  THE01110
      FUNCTION DIREC2,-8.0=(-15.,.070),(-10.,.050),(-5.,.026),...        THE01120
      (0.0,0.0),(5.,-.022),(10.,-.052),(15.,-.080)                       THE01130
      FUNCTION DIREC2, 2.0=(-15.,.068),(-10.,.049),(-5.,.024),...        THE01140
      (0.0,0.0),(5.,-.020),(10.,-.048),(15.,-.079)                       THE01150
      FUNCTION DIREC2, 6.0=(-15.,.062),(-10.,.048),(-5.,.022),...        THE01160
      (0.0,-.001),(5.,-.018),(10.,-.047),(15.,-.074)                     THE01170
      FUNCTION DIREC2, 8.0=(-15.,.065),(-10.,.048),(-5.,.018),...        THE01180
      (0.0,-.003),(5.,-.014),(10.,-.046),(15.,-.075)                     THE01190
*     ALFA VS RUDDER VS DELTA CROLLST(RUD)                               THE01200
      FUNCTION DIREC3,-8.0=(-15.,-.0050),(-10.,-.0034),(-5.,-.0018),...  THE01210
      (0.0,.0004),(5.,.0024),(10.,.0048),(15.,.0070)                     THE01220
      FUNCTION DIREC3, 2.0=(-15.,-.0038),(-10.,-.0029),(-5.,-.0018),...  THE01230
      (0.0,0.0),(5.,.0012),(10.,.0028),(15.,.0053)                       THE01240
      FUNCTION DIREC3, 4.0=(-15.,-.0033),(-10.,-.0027),(-5.,-.0018),...  THE01250
      (0.0,-.0004),(5.,0.),(10.,.0012),(15.,.0040)                       THE01260
      FUNCTION DIREC3, 7.0=(-15.,-.002),(-10.,-.002),(-5.,-.002),...     THE01270
      (0.,-.002),(5.,-.002),(10.,-.002),(15.,-.002)                      THE01280
      FUNCTION DIREC3, 8.0=(-15.,-.0014),(-10.,-.0018),(-5.,-.0020),...  THE01290
      (0.,-.0032),(5.,-.0038),(10.,-.0041),(15.,-.0048)                  THE01300
*     LATERAL CONTROL CHARACTERISTICS                                    THE01310
*     ALFA VS AILERON VS DELTA CYST(AIL)                                 THE01320
      FUNCTION LATRL1, -8.0=(-15.,.015),(-10.,.013),(-5.,.010),...       THE01330
      (0.,.007),(5.,.002),(10.,-.005),(15.,-.010)                        THE01340
      FUNCTION LATRL1, -1.0=(-15.,.019),(-10.,.014),(-5.,.009),...       THE01350
      (0.,.002),(5.,-.003),(10.,-.009),(15.,-.014)                       THE01360
      FUNCTION LATRL1,  4.0=(-15.,.017),(-10.,.010),(-5.,.002),...       THE01370
      (0.,-.007),(5.,-.014),(10.,-.020),(15.,-.025)                      THE01380
      FUNCTION LATRL1, 10.0=(-15.,.006),(-10.,-.002),(-5.,-.010),...     THE01390
      (0.,-.018),(5.,-.026),(10.,-.033),(15.,-.042)                      THE01400
*     ALFA VS AILERON VS DELTA CNST(AIL)                                 THE01410
      FUNCTION LATRL2, -8.0=(-15.,.0075),(-10.,.0040),(-5.,.0015),...    THE01420
      (0.,-.0020),(5.,-.0070),(10.,-.0120),(15.,-.0175)                  THE01430
      FUNCTION LATRL2, -4.0=(-15.,.0050),(-10.,.0030),(-5.,.0020),...    THE01440
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      (0.,-.0010),(5.,-.0030),(10.,-.0045),(15.,-.0070)                 THE01450
      FUNCTION LATRL2, 0.0=(-15.,0.),(-10.,0.),(-5.,0.),(0.,0.),...     THE01460
      (5.,0.),(10.,0.),(15.,0.)                                         THE01470
      FUNCTION LATRL2, 4.0=(-15.,-.0075),(-10.,-.0050),(-5.,-.0025),... THE01480
      (0.0,-.0008),(5.,.0025),(10.,.0040),(15.,.0070)                   THE01490
      FUNCTION LATRL2, 8.0=(-15.,-.0120),(-10.,-.0085),(-5.,-.0060),... THE01500
      (0.0,-.0020),(5.,.0050),(10.,.0120),(15.,.0175)                   THE01510
*     ALFA VS AILERON VS DELTA CROLLST(AIL)                             THE01520
      FUNCTION LATRL3, -8.0=(-15.,.0087),(-10.,.0060),(-5.,.0030),....  THE01530
      (0.,.0004),(5.,-.0008),(10.,-.0018),(15.,-.0030)                  THE01540
      FUNCTION LATRL3, -4.0=(-15.,.0096),(-10.,.0066),(-5.,.0033),....  THE01550
      (0.,.0004),(5.,-.0023),(10.,-.0059),(15.,-.0080)                  THE01560
      FUNCTION LATRL3,  0.0=(-15.,.0100),(-10.,.0068),(-5.,.0034),....  THE01570
      (0.0,.0004),(5.,-.0030),(10.,-.0072),(15.,-.0092)                 THE01580
      FUNCTION LATRL3,  4.0=(-15.,.0092),(-10.,.0064),(-5.,.0036),....  THE01590
      (0.0,-.0004),(5.,-.0030),(10.,-.0046),(15.,-.0088)                THE01600
      FUNCTION LATRL3,  8.0=(-15.,.0084),(-10.,.0058),(-5.,.0030),....  THE01610
      (0.0,-.0004),(5.,-.0020),(10.,-.0040),(15.,-.0050)                THE01620
*                                                                       THE01630
      DYNAMIC                                                           THE01640
      NOSORT                                                            THE01650
      IF (TIME.EQ.0.0) RNGMIN =100.0                                    THE01660
      IF (RNGMIN.LE.RANGE) GO TO 10                                     THE01670
         RNGMIN = RANGE                                                 THE01680
         TIMMIN = TIME                                                  THE01690
         DXTGTM = DXTGT                                                 THE01700
         DYTGTM = DYTGT                                                 THE01710
         DZTGTM = DZTGT                                                 THE01720
 10   CONTINUE                                                          THE01730
*     ALGORITHM THAT PROCEEDS FROM INGRESS TO 17800,RIGHT OFFSET TO     THE01740
*     15800, LEVEL OFF TO 10200, POP UP TO 9100, ATTACK UNTIL HIT       THE01750
         IF(RANGE.GT.17800.0) GO TO 20                                  THE01760
         IF(RANGE.GT.15800.0) GO TO 30                                  THE01770
         IF(RANGE.GT.10200.0) GO TO 40                                  THE01780
         IF(RANGE.GT.9100.0) GO TO 50                                   THE01790
         IF(RANGE.GT.0.0) GO TO 60                                      THE01800
*     INGRESS INTO 17800.0 FEET                                         THE01810
 20         DXTGT = XT-XEARTH                                           THE01820
            DYTGT = YT-YEARTH                                           THE01830
            DZTGT = HT-ALTUDE                                           THE01840
            AYC = LAMDAZ*VT*SIGDZ1/G                                    THE01850
            ANC = AZC*COS(PHI)+AYC*SIN(PHI)                             THE01860
            IF(AYC.EQ.0.0.AND.AZC.EQ.0.0) PHIC = 0.0                    THE01870
            IF(AYC.NE.0.0.OR.AZC.NE.0.0) PHIC=ATAN2(AYC,AZC)            THE01880
            PHIC1 = LIMIT(-1.047,1.047,PHIC)                            THE01890
         GO TO 200                                                      THE01900
*     TURN TO RIGHT UNTIL TARGET AZIMUTH ANGLE = 12 DEGREES(SIGAZ)      THE01910
 30         DXTGT = XT-XEARTH                                           THE01920
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      DYTGT = YT-YEARTH                                                 THE01930
      DZTGT = HT-ALTUDE                                                 THE01940
      ANC = AZC/COS(PHI)                                                THE01950
         PHIC1 = 1.047                                                  THE01960
      GO TO 200                                                         THE01970
*    COMMAND ZERO DEGREES BANK ANGLE UNTIL START OF POP UP              THE01980
 40   DXTGT = XT-XEARTH                                                 THE01990
      DYTGT = YT-YEARTH                                                 THE02000
      DZTGT = HT-ALTUDE                                                 THE02010
      ANC = AZC/COS(PHI)                                                THE02020
         PHIC1 = 0.0                                                    THE02030
      GO TO 200                                                         THE02040
*    POP UP UNTIL ALTUDE = 250 FEET                                     THE02050
 50   DXTGT = XT-XEARTH                                                 THE02060
      DYTGT = YT-YEARTH                                                 THE02070
      DZTGT = HT-ALTUDE                                                 THE02080
      AYC = LAMDAZ*VT*SIGDZ1/G                                          THE02090
      ANC = AZCP*COS(PHI)+AYC*SIN(PHI)                                  THE02100
      PHIC = ATAN2(AYC,AZCP)                                            THE02110
      PHIC1 = LIMIT(-1.047,1.047,PHIC)                                  THE02120
   GO TO 200                                                            THE02130
*    ATTACK PHASE INTO THE TARGET                                       THE02140
 60     IF (RANGE.GT.9000.0) GO TO 65                                   THE02150
        IF (RANGE.LT.2000.) GO TO 65                                    THE02160
*    ALLOW ECM TO OCCUR BETWEEN 9000 AND 2000 FT RANGE                  THE02170
*    PUT ECM BLINKING OF 75FT HORIZONTAL SHIFT AT FREQ(.5,1,2 CPS)      THE02180
        Y1 = SIN(2*PI*FREQ*TIME)                                        THE02190
        YY = INSW(Y1,SHIFTY,0.0)                                        THE02200
        YTT = YT-YY                                                     THE02210
*    PUT ECM BLINKING OF 15FT VERTICAL SHIFT AT FREQ(.5,1,2 CPS)        THE02220
        H1 = SIN(2*PI*FREQ*TIME)                                        THE02230
        HH = INSW(H1,SHIFTH,0.0)                                        THE02240
        HTT = HT+HH                                                     THE02250
        DXTGT = XT-XEARTH                                               THE02260
        DYTGT = YTT-YEARTH                                              THE02270
        DZTGT = HTT-ALTUDE                                              THE02280
        GO TO 66                                                        THE02290
 65     DXTGT = XT-XEARTH                                               THE02300
        DYTGT = YT-YEARTH                                               THE02310
        DZTGT = HT-ALTUDE                                               THE02320
*    PROPORTIONAL ELEVATION                                             THE02330
 66          PNEL1 = LAMDEL*VT*SIGDE1/G                                 THE02340
             AZCPR3 = PNEL1 + 1.0                                       THE02350
             AYC = LAMDAZ*VT*SIGDZ1/G                                   THE02360
             ANC = AZCPR3*COS(PHI)+AYC*SIN(PHI)                         THE02370
             PHIC1 = ATAN2(AYC,AZCPR3)                                  THE02380
*            THIS ROUTINE KEEPS PHIC FROM ROTATING 360 DEG WHEN         THE02390
*            TAN FUNCTION PASSES THROUGH 180 DEG.                       THE02400
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            DELTA =  PHIC1-PHI                                            THE02410
            DELTA1 = ABS(DELTA)                                           THE02420
            IF (DELTA1.LT.3.141592654) GO TO 200                          THE02430
            IF (PHIC1.GE.0.0) GO TO 70                                    THE02440
            PHIC1 = PHIC1 + 6.2831853                                     THE02450
            GO TO 200                                                     THE02460
70          PHIC1 = PHIC1 - 6.2831853                                     THE02470
200   CONTINUE                                                            THE02480
      SORT                                                                THE02490
      QS =12.0*.002377*(VT**2)/2                                          THE02500
      PHIDOT = P+TAN(THETA)*(Q*SIN(PHI)+R*COS(PHI))                       THE02510
      THETAD = Q*COS(PHI)-R*SIN(PHI)                                      THE02520
      SYDOT = (Q*SIN(PHI)+R*COS(PHI))/COS(THETA)                          THE02530
      PHI = INTGRL(0.0,PHIDOT)                                            THE02540
      THETA = INTGRL(0.04880,THETAD)                                      THE02550
      SY = INTGRL(0.0,SYDOT)                                              THE02560
      UDOT = -G*SIN(THETA)+V*R-W*Q+X/M+T/M                                THE02570
      VDOT = G*SIN(PHI)*COS(THETA)-U*R+W*P+Y/M                            THE02580
      WDOT = G*COS(PHI)*COS(THETA)+U*Q-V*P+Z/M                            THE02590
      U = INTGRL(838.1,UDOT)                                              THE02600
      V = INTGRL(0.0,VDOT)                                                THE02610
      W = INTGRL(38.79,WDOT)                                              THE02620
      XEDOT= U*COS(SY)*COS(THETA)+V*(COS(SY)*SIN(THETA)*SIN(PHI)...       THE02630
      -SIN(SY)*COS(PHI))+W*(COS(SY)*SIN(THETA)*COS(PHI)+...               THE02640
      SIN(SY)*SIN(PHI))                                                   THE02650
      YEDOT=U*SIN(SY)*COS(THETA)+V*(SIN(SY)*SIN(THETA)*SIN(PHI)...        THE02660
      +COS(SY)*COS(PHI))+W*(SIN(SY)*SIN(THETA)*COS(PHI)-...               THE02670
      COS(SY)*SIN(PHI))                                                   THE02680
      ZEDOT= U*SIN(THETA)-V*COS(THETA)*SIN(PHI)-W*COS(THETA)*COS(PHI)     THE02690
      XEARTH=INTGRL(0.0,XEDOT)                                            THE02700
      YEARTH=INTGRL(0.0,YEDOT)                                            THE02710
*     NOTE: ALTUDE AND Z FUNCTIONS ARE DEFINED AS POSITIVE GOING UP       THE02720
      ALTUDE=INTGRL(50.,ZEDOT)                                            THE02730
      PDOT = 0.036089*LA+0.000279*NA+0.009160*P*Q-0.183711*R*Q            THE02740
      RDOT = 0.000279*LA+0.000664*NA-0.978236*P*Q-0.009160*R*Q            THE02750
      QDOT = (MA+1484.2*P*R-11.7*(P**2-R**2))/1507.0                      THE02760
      P = INTGRL(0.0,PDOT)                                                THE02770
      Q = INTGRL(0.0,QDOT)                                                THE02780
      R = INTGRL(0.0,RDOT)                                                THE02790
      ALFA=ATAN(W/U)                                                      THE02800
      BETA=ASIN(V/VT)                                                     THE02810
      ALFADT=DERIV(0.04880,ALFA)                                          THE02820
      BETADT=DERIV(0.0,BETA)                                              THE02830
      VT=SQRT(U**2+V**2+W**2)                                             THE02840
      CLBAS=FUNGEN(LIFT1,1,ALFA1)                                         THE02850
      DCLSTE=FUNGEN(LIFT2,1,ELE1)                                         THE02860
      CDBAS=FUNGEN(DRAG1,1,CLBAS)                                         THE02870
      DCDSTE=FUNGEN(DRAG2,1,ELE1)                                         THE02880
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      DCDSTA=FUNGEN(DRAG3,1,AIL1)                                        THE02890
      DCDSTR=FUNGEN(DRAG4,1,RUD1)                                        THE02900
      CMBAS=FUNGEN(PITCH1,1,ALFA1)                                       THE02910
      DCMSTE=FUNGEN(PITCH2,1,ELE1)                                       THE02920
      CYBAS=TWOVAR(SIDE1,BETA1,ALFA1)                                    THE02930
      CRBAS=TWOVAR(SIDE2,BETA1,ALFA1)                                    THE02940
      CNBAS=TWOVAR(SIDE3,BETA1,ALFA1)                                    THE02950
      DCYSTR=TWOVAR(DIREC1,RUD1,ALFA1)                                   THE02960
      DCNSTR=TWOVAR(DIREC2,RUD1,ALFA1)                                   THE02970
      DCRSTR=TWOVAR(DIREC3,RUD1,ALFA1)                                   THE02980
      DCYSTA=TWOVAR(LATRL1,AIL1,ALFA1)                                   THE02990
      DCNSTA=TWOVAR(LATRL2,AIL1,ALFA1)                                   THE03000
      DCRSTA=TWOVAR(LATRL3,AIL1,ALFA1)                                   THE03010
      CL=CLBAS+DCLSTE+.707/VT*(2.0*ALFADT+5.0*Q)                         THE03020
      CD=CDBAS+DCDSTE+DCDSTA+DCDSTR+.707/VT*(0.1*ALFADT+0.1*Q)           THE03030
      CY=CYBAS+DCYSTR+DCYSTA+4.24/VT*(0.40*R-0.10*P-0.10*BETADT)         THE03040
      CM=CMBAS+DCMSTE+0.707/VT*(-10.0*ALFADT-15.0*Q)                     THE03050
      CN=CNBAS+DCNSTR+DCNSTA+4.24/VT*(0.15*BETADT-0.20*R-0.01*P)         THE03060
      CROLL=CRBAS+DCRSTA+DCRSTR+4.24/VT*(0.20*R-0.40*P)                  THE03070
      L=CL*QS                                                            THE03080
      D=CD*QS                                                            THE03090
      LA=8.485*CROLL*QS                                                  THE03100
      MA=1.414*CM*QS                                                     THE03110
      NA=8.485*CN*QS                                                     THE03120
      X=L*SIN(ALFA)-D*COS(ALFA)                                          THE03130
      Y=CY*QS                                                            THE03140
      Z=-L*COS(ALFA)-D*SIN(ALFA)                                         THE03150
      NZLOAD=-Z/(M*G)                                                    THE03160
      NYLOAD=Y/(M*G)                                                     THE03170
      ALFA1=ALFA*K2                                                      THE03180
      BETA1=BETA*K2                                                      THE03190
      PHI1=PHI*K2                                                        THE03200
      THETA1=THETA*K2                                                    THE03210
      P1=P*K2                                                            THE03220
      Q1=Q*K2                                                            THE03230
      R1=R*K2                                                            THE03240
      SY1=SY*K2                                                          THE03250
      ELE1=ELE*K2                                                        THE03260
      RUD1=RUD*K2                                                        THE03270
      AIL1=AIL*K2                                                        THE03280
      GAMMA1=GAMMA*K2                                                    THE03290
*                                                                        THE03300
*     INNER LOOP AUTOPILOT                                               THE03310
*                                                                        THE03320
*     NORMAL ACCELERATION COMMAND                                        THE03330
*                                                                        THE03340
      ANC1 = LIMIT(-2.0,4.0,ANC)                                         THE03350
      ERRORN = ANC1-(NZLOAD+C*QDOT/G)                                    THE03360
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      NSERVI =-1.0*(KA1*INTGRL(0.0,ERRORN)-KR1*Q)                       THE03370
      NSERVO = REALPL(0.0,0.025,NSERVI)                                 THE03380
      ELE = LIMIT(-0.262,0.262,NSERVO)                                  THE03390
*                                                                       THE03400
*     BANK ANGLE COMMAND SYSTEM                                         THE03410
*     60 DEGREE LIMIT ON BANK ANGLE = 1.047 RADIANS(DONE IN ALGORITHM)  THE03420
*     ROLL RATE (PCL) IS VARIED AS 50,100,&200 DEG/SEC                  THE03430
*     50=.87,  100=1.75,  200=3.49                                      THE03440
*                                                                       THE03450
      ERRBA1 = (PHIC1-PHI)*KD                                           THE03460
      PCL = LIMIT(-1.75,1.75,ERRBA1)                                    THE03470
      PCL1 = PCL*K2                                                     THE03480
      PHIC2 = PHIC1*K2                                                  THE03490
      BASRVI = -1.0*KR2*(PCL-P)                                         THE03500
      BASRVO = REALPL(0.0,0.025,BASRVI)                                 THE03510
      AIL = LIMIT(-0.262,0.262,BASRVO)                                  THE03520
*                                                                       THE03530
*     TURN COORDINATOR                                                  THE03540
*                                                                       THE03550
      ALC = 0.0                                                         THE03560
      EN = ALC-(C*RDOT/G+NYLOAD)                                        THE03570
      EN1= KA2*(INTGRL(0.0,EN))                                         THE03580
      TSERVI = -1.0*(EN1-KR3*R)                                         THE03590
      TSERVO = REALPL(0.0,0.025,TSERVI)                                 THE03600
      RUD = LIMIT(-0.262,0.262,TSERVO)                                  THE03610
*                                                                       THE03620
*     GUIDANCE.                                                         THE03630
*                                                                       THE03640
*     GUIDANCE SCHEME IS DIVIDED INTO FOUR PHASES-INGRESS,TURN,POP UP,  THE03650
*     AND ATTACK.  PROPORTIONAL NAVIGATION IS USED FOR HEADING CONTROL  THE03660
*     DURING INGRESS AND POP UP (BOTH WITH BANK ANGLE LIMITED TO 60 DEG)THE03670
*     AND DURING ATTACK PHASE (BANK ANGLE UNLIMITED). DURING THE TURN   THE03680
*     PHASE THE HEADING COMMANDS ARE ACHIEVED WITH FIXED BANK ANGLES.   THE03690
*     AN ALTITUDE HOLD OF 50 FEET IS USED FOR INGRESS AND TURN PHASES.  THE03700
*     VERTICAL FLIGHT PATH ANGLE CONTROL (CONSTANT RATE OF CLIMB OF 8.6 THE03710
*     DEGREES IS USED FOR THE POP UP MANEUVER).                         THE03720
*                                                                       THE03730
*     OUTER LOOP AUTOPILOT                                              THE03740
*     FLIGHT PATH ANGLE                                                 THE03750
      AZC = 1.0+KGAMMA*VT/G*(GAMMAC-GAMMA)                              THE03760
      GAMMA = ASIN(ZEDOT/VT)                                            THE03770
*     ALTITUDE HOLD                                                     THE03780
      ALTCMD = 50.0                                                     THE03790
      GAMMAC = KALT/VT*(ALTCMD-ALTUDE)                                  THE03800
*     POP UP MANEUVER (CLIMB ANGLE=CLIMBA=8.6 DEGREES)                  THE03810
      AZCP = 1.0+KGAMMA*VT/G*(CLIMBA-GAMMA)                             THE03820
*                                                                       THE03830
*     SEEKER EQUATIONS                                                  THE03840
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*                                                                       THE03850
      YT2 = YTI+35.0*TIME                                               THE03860
      RANGE  = SQRT((XTI-XEARTH)**2+(YT2-YEARTH)**2+(HTI-ALTUDE)**2)    THE03870
      SIGDZB = -SIGDEL*SIN(PHI)+SIGDAZ*COS(THETA)*COS(PHI)              THE03880
      SIGDEB = SIGDEL*COS(PHI)+SIGDAZ*COS(THETA)*SIN(PHI)               THE03890
      SIGDZ1 = SIGDZB*COS(PHI)+SIGDEB*SIN(PHI)                          THE03900
      SIGDE1 = -SIGDZB*SIN(PHI)+SIGDEB*COS(PHI)                         THE03910
*     THIS SECTION CHANGES PROGRAM VARIABLES TO MORE COMMON NAMES       THE03920
      XRANGE = ABS(XTI-XEARTH)                                          THE03930
      YRANGE = ABS(YT2-YEARTH)                                          THE03940
      ZRANGE = ABS(HTI-ALTUDE)                                          THE03950
      PCMD = PCL1                                                       THE03960
      PHICMD = PHIC2                                                    THE03970
      XMISLE = XEARTH                                                   THE03980
      YMISLE = YEARTH                                                   THE03990
      HMISLE = ALTUDE                                                   THE04000
      XTGT = XTI                                                        THE04010
      YTGT = YT2                                                        THE04020
      HTGT = HTI                                                        THE04030
      YECM = YTT                                                        THE04040
      HECM = HTT                                                        THE04050
      RUDDER = RUD1                                                     THE04060
      L1STAB = ELE1-AIL1                                                THE04070
      R1STAB = ELE1+AIL1                                                THE04080
      NZ = NZLCAD                                                       THE04090
      NZ1CMD = ANC1                                                     THE04100
      NY = NYLCAD                                                       THE04110
      NY1CMD = ALC                                                      THE04120
      ELLCSR = SIGDEL*K2                                                THE04130
      AZLCSR = SIGDAZ*K2                                                THE04140
*                                                                       THE04150
      THETDT = (-ZEDOT*(DXTGT**2+DYTGT**2)-DZTGT*(-XEDOT*DXTGT+...      THE04160
      (35.0-YEDOT)*DYTGT))/(RANGE**2*SQRT(DXTGT**2+DYTGT**2))           THE04170
      THETDF = REALPL(0.0,10.,THETAD)                                   THE04180
      SIGDEL = THETDT-THETDF                                            THE04190
      SYDOTT =(XEDOT*DYTGT+(35.-YEDOT)*DXTGT)/(DXTGT**2+DYTGT**2)       THE04200
      SYDOTF = REALPL(0.0,10.0,SYDOT)                                   THE04210
      SIGDAZ = SYDOTT-SYDOTF                                            THE04220
*                                                                       THE04230
*     TARGET GLINT FACTOR WITH SHIP MOVING AT 21 KNOTS TO EAST          THE04240
*     YTR= GAUSS(5,0.0,20.0)                                            THE04250
*     XTR = GAUSS(3,0.0,6.0)                                            THE04260
*     HTR = GAUSS(1,0.0,6.0)                                            THE04270
*     XT  = XTI+XTR                                                     THE04280
*     YT  = YT2+YTR                                                     THE04290
*     HT  = HTI+HTR                                                     THE04300
      XT  = XTI                                                         THE04310
      YT  = YT2                                                         THE04320
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      HT = HTI                                                            THE04330
*                                                                         THE04340
      NOSCRT                                                              THE04350
      CALL DEBUG(1,30.16)                                                 THE04360
      CALL DEBUG(1,30.17)                                                 THE04370
      CALL DEBUG(1,30.18)                                                 THE04380
      CALL DEBUG(1,30.19)                                                 THE04390
      CALL DEBUG(1,30.20)                                                 THE04400
      CALL DEBUG(1,30.21)                                                 THE04410
      CALL DEBUG(1,30.22)                                                 THE04420
      CALL DEBUG(1,30.23)                                                 THE04430
      CALL DEBUG(1,30.24)                                                 THE04440
      CALL DEBUG(1,30.25)                                                 THE04450
      CALL DEBUG(1,30.26)                                                 THE04460
      TERMINAL                                                            THE04470
      OUTPUT TIMMIN,RNGMIN,DXTGTM,DYTGTM,DZTGTM                           THE04480
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      OUTPUT TIME,PHI1(-180.0,180.0),PHICMD(-180.0,180.0)                 THE04550
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      YRANGE(-400.,2800.),ZRANGE(-40.,280.)                               THE04590
      LABEL RANGE,XRANGE,YRANGE,ZRANGE (FEET) VS TIME                     THE04600
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*     YRANGE(0.,80.),ZRANGE(0.,80.)                                       THE04630
*     LABEL RANGE,XRANGE,YRANGE,ZRANGE (FEET) VS TIME                     THE04640
*     PAGE XYPLOT                                                         THE04650
*     OUTPUT TIME,XMISLE(0.,32000.0),XTGT(0.,32000.0)                     THE04660
*     LABEL MISSILE AND TARGET X COORDINATE (FEET) VS TIME                THE04670
*     PAGE XYPLOT                                                         THE04680
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*     LABEL MISSILE AND TARGET ALTITUDE (FEET) VS TIME                    THE04730
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      PAGE XYPLOT                                                         THE04770
      OUTPUT TIME,RUDDER(-20.,20.)                                        THE04780
      LABEL RUDDER POSITION (DEGREES) VS TIME                             THE04790
      PAGE XYPLOT                                                         THE04800
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*     OUTPUT TIME,NZ(-3.,5.),NZ1CMD(-3.,5.)                             THE04810
*     LABEL VERTICAL ACCELERATION (G'S) VS TIME                         THE04820
*     PAGE XYFLCT                                                       THE04830
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*     LABEL HCRIZCNTAL ACCELERATION (G'S) VS TIME                       THE04850
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      LABEL MAP OF YMISLE AND HMISLE VS XMISLE  (FEET)                  THE04910
      PAGE XYFLOT                                                       THE04920
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      STOP                                                              THE04940
ENDJCB                                                                  THE04950
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